University of Southern Queensland

Faculty of Engineering and Surveying

Investigate the Use of Thermal Protection for Underground Cables in Ergon Energy's Electricity Network

A dissertation submitted by

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Abstract

To transmit power through an electricity transmission or distribution network is by either overhead power lines or power cables. Overhead lines are the initial and usual option as cost can be greatly reduced. Cables are more reliable as they are less impacted by weather and other environmental influences than overhead lines. They also take up less space than the alternative option.

The continued growth of consumer electricity use in Queensland, has led electricity service providers in subjecting a substantial amount of existing assets to a high utilisation ratio, even into overload to cope with the demand. Until system augmentation and further capital works are implemented to introduce greater capacity to their network, technical and engineering staffs are tasked to manipulate this network while attempting to maintaining electricity supply and reducing risk to safety and plant.

To achieve the higher utilisation of assets, the method of dynamic rating of plant enables the electricity utility the ability to provide consumers both new and old with supply until further capital and system augmentation works are carried out. This project is aimed at developing a model that can be used in reality to assist in the ability to employ dynamic ratings of cables taking into account the varying parameters that dictate the current capability of power cables.

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Glossary

AC: Alternating Current.

Ampacity: A term given for the current capacity of a cable.

DC: Direct Current.

DTS: Distributed Temperature Sensing, a method where a fibre optic cable is used to measure temperature along a length of cable continuously.

DNSP: Is a distribution network service provider like Ergon Energy Corporation or Energex Corporation who manage the supply of electricity to customers. They are also referred to as Electricity Entities or Electricity Service Provider.

EMF: Electrical and Magnetic Fields. It has also been used for an abbreviation for electro-magnetic force.

High voltage: relates to voltages greater than 1000 Volts.

HV: see High Voltage.

ICNIRP: International Commission on Non-Ionizing Radiation Protection.

IEC: International Electrotechnical Commission.

IEEE: The Institute of Electrical and Electronic Engineers.

kA: kiloampere = 1000 amperes.

kV: kilovolt = 1000 volts.

MW: Megawatt = 1000000 watts.

PLYS: Paper Lead Alloy Sheathed.

SCADA: System Control and Data Acquisition. An electronic system used to monitor and control elements of a process or network.

Thermal resistivity: the ability to dissipate heat.

Thermal capacitiance: the material's ability to store heat.

TNSP: Is a transmission network service provider like Powerlink Queensland Corporation who manage the supply of electricity at high voltage to DNSP's

XLPE: cross-linked polyethylene

Symbology

A	cross-sectional area of the armour	mm²
$B1$	$\omega(H_s + H_1 + H_3)$	Ω/m
$B2$	ωH_2	Ω/m
C	capacitance per core	F/m
D_e^*	external diameter of cable	m
D_i	diameter over insulation	mm
D_s	external diameter of metal sheath	mm
D_{oc}	the diameter of the imaginary coaxial cylinder which just touches the crests of a corrugated sheath	mm
D_{it}	the diameter of the imaginary cylinder which just touches the inside surface of the troughs of a corrugated sheath	mm
H	intensity of solar radiation	W/m²
H	magnetizing force	ampere turns/m
H_s	inductance of sheath	H/m
$\left.\begin{matrix} H_1 \\ H_2 \\ H_3 \end{matrix}\right\}$	components of inductance due to the steel wires (see 2.4.2)	H/m
I	current in one conductor (r.m.s. value)	A
M	cyclic rating factor	

R	alternating current resistance of conductor at its maximum operating temperature	Ω/m
R_A	a.c. resistance of armour	Ω/m
R_e	equivalent a.c. resistance of sheath and armour in parallel	Ω/m
R_s	a.c. resistance of sheath	Ω/m
R'	d.c. resistance of conductor at maximum operating temperature	Ω/m
R_o	d.c. resistance of conductor at 20 °C	Ω/m
T_1	thermal resistance per core between conductor and sheath	K.m/W
T_2	thermal resistance between sheath and armour	K.m/W
T_3	thermal resistance of external serving	K.m/W
T_4	thermal resistance of surrounding medium (ratio of cable surface temperature rise above ambient to the losses per unit length)	K.m/W
T_4^*	external thermal resistance in free air, adjusted for solar radiation	K.m/W
U_o	voltage between conductor and screen or sheath	V
W_a	losses in armour per unit length	W/m
W_c	losses in conductor per unit length	W/m
W_d	dielectric losses per unit length per phase	W/m
W_s	losses dissipated in sheath per unit length	W/m
$W_{(s+A)}$	total losses in sheath and armour per unit length	W/m
X	reactance of sheath (two-core cables and three-core cables in trefoil)	Ω/m
X_1	reactance of sheath (cables in flat formation)	Ω/m

X_m	mutual reactance between the sheath of one cable and the conductors of the other two when cables are in flat information	Ω/m
a	shortest minor length in a cross-bonded electrical section having unequal minor lengths	
c	distance between the axes of conductors and the axis of the cable for three-core cables (=$0.55r_1 + 0.29t$ for sector-shaped conductors)	mm
d	mean diameter of sheath or screen	mm
d'	mean diameter of sheath and reinforcement	mm
d_2	mean diameter of reinforcement	mm
d_A	mean diameter of armour	mm
d_c	external diameter of conductor	mm
d'_c	external diameter of equivalent round solid conductor having the same central duct as a hollow conductor	mm
d_d	internal diameter of pipe	mm
d_f	diameter of a steel wire	mm
d_i	internal diameter of hollow conductor	mm
d_M	major diameter of screen or sheath of an oval conductor	mm
d_m	minor diameter of screen or sheath of an oval conductor	mm
d_x	diameter of an equivalent circular conductor having the same cross-sectional area and degree of compactness as the shaped one	mm
f	system frequency	Hz
k	factor used in the calculation of hysteresis losses in armour or	

	reinforcement (see 2.4.2.4)	
k_p	factor used in calculating x_p (proximity effect)	
k_s	factor used in calculating x_s (skin effect)	
l	length of a cable section (general symbol)	m
ln	natural logarithm (logarithm to base e)	
m	$\frac{\omega}{R_s}10^{-7}$	
n	number of conductors in a cable	
n_n	number of wires in layer n of a cable	
p	length of lay of a steel wire along a cable	
r_1	circumscribing radius of two-or three-sector shaped conductors	mm
s	axial separation of conductors	mm
s_1	axial separation of two adjacent cables in a horizontal group of three, not touching	mm
s_2	axial separation of cables	mm
t	insulation thickness between conductors	mm
t_3	thickness of the serving	mm
t_s	thickness of the sheath	mm
v	ratio of the thermal resistivities of dry and moist soils $\left(v = \rho d / \rho_w\right)$	
x_p	argument of a Bessel function used to calculate proximity effect	
x_s	argument of a Bessel function used to calculate skin effect	

y_p	proximity effect factor	
y_s	skin effect factor	
α_{20}	temperature coefficient of electrical resistivity at 20 °C, per kelvin	I/K
β	angle between axis of armour wires and axis of cable	
γ	angular time delay	
δ	equivalent thickness of armour or reinforcement	mm
$tan\ \delta$	loss factor of insulation	
ε	relative permittivity of insulation	
θ	maximum operating temperature of conductor	°C
θ_a	ambient temperature	°C
θ_x	critical temperature of soil; this is the temperature of the boundary between dry and moist zones	°C
$\Delta\theta$	permissible temperature rise of conductor above ambient temperature	K
$\Delta\theta_x$	critical temperature rise of soil; this is the temperature rise of the boundary between dry and moist zones above the ambient temperature of the soil	K
$\lambda_1\ \lambda_2$	ratio of the total losses in metallic sheaths and armour respectively to the total conductor losses (or losses in one sheath or armour to the losses in one conductor)	
$\lambda_1^{'}$	ratio of the losses in one sheath caused by circulating currents in the sheath to the losses in one conductor	
$\lambda_1^{''}$	ratio of the losses in one sheath caused by eddy currents to the losses in one conductor	

λ'_{1m}	loss factor for the middle cable	
λ'_{11}	loss factor for the outer cable with the greater losses loss factor for the outer cable with the greater losses	
λ'_{12}	loss factor for the outer cable with the greater losses loss factor for the outer cable with the least losses	
μ	relative magnetic permeability of armour material	
μ_e	longitudinal relative permeability	
μ_t	transverse relative permeability	
ρ	conductor resistivity at 20 °C	Ω.m
ρ_d	thermal resistivity of dry soil	K.m/W
ρ_w	thermal resistivity of moist soil	K.m/W
ρ_s	sheath resistivity at 20 °C	Ω.m
σ	absorption coefficient of solar radiation for the cable surface	
ω	angular frequency of system (2πf)	

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Chapter 1 - Introduction

1.1. Background

The continued growth of consumer electricity use in Queensland, has led electricity service providers in subjecting a substantial amount of existing assets to a high utilisation ratio, even into overload to cope with the demand. This demand increase is due varying factors including increasing population, mineral resource boom (includes mines and smelters) and the affordability of white goods, the list is not exhaustive but indicative.

In the last decade, electricity consumption in Queensland has increased 53 percent to an annual usage of 8200 MW. This consumption rates Queensland as the second highest electricity user in Australia (Queensland Department of Energy 2006). The electricity network in the state composes of three distinct tiers, generation providers, transmission network services provider (TNSP) and distribution network service providers (DNSP).

The ability to transmit the electricity to the consumer via the transmission or distribution network is by either overhead power lines or power cables. Overhead lines are the initial and usual option as cost can be greatly reduced from the materials used and resources required to install the transporting medium. However, cables are more reliable as they are less impacted by weather and other environmental influences than overhead lines. They also take up less space than the alternative option. Since the majority of the cables that Ergon Energy (approximately 99 percent) has in the network are high voltage, the focus of this project is dealing with these HV cables.

To enable the continued uninterrupted supply to the end user and ensuring quality of supply is not affected, system augmentation and the introduction of new capital works are being implemented to introduce greater capacity to their network. This also includes replacing aged assets that have passed their ‘use by date’. Until these works are in situ, technical and engineering staffs are tasked to manipulate the electricity network to get the most out of these assets while attempting to maintaining electricity supply and reducing risk to safety and plant. It is this area of the network, we will be investigating the management of power cables and ensuring that they can be utilised to their fullest without degradation or destruction of the cable.

1.2. Project Objectives

It is proposed that this project fulfil the following aims;

1. Research background information on the theory of heating of cables, the issues and the effects. Research information on the current Australian and Ergon Energy's Standards to the thermal rating of cables that are being used and the effect of the varying methods of enclosures for cables.

2. Collate the feeder cable temperatures that are being monitored at an Ergon Substation and the type of enclosures i.e. the soil backfill, type of cable and its properties also the ambient and ground temperatures.

3. Compare the data collected in (2) and compare the results with existing software packages in use in Ergon.

4. Research and understand the capabilities of the Schweitzer SEL Protection Relays for possible thermal protection implementation.

5. Develop a mathematical model to predict the temperature curve to suit the varying parameters such as the type of cable, the soil properties, the load curve for the cable and other environmental factors such as air and ground temperatures to use in the protection relay.

If time permits

6. If in (5) it is not possible for the relay to employ the thermal protection, then review the possibility of the SCADA RTUs to facilitate the function.

7. Programme the SEL-3?? Relays for thermal protection and test.

8. Evaluate the possibility of extending the use of the model in (5) above to other protection relays in Ergon's network.

1.3. Impact to Ergon Energy

As the network grows some of the existing equipment are then subjected to higher loads and greater fault levels. In the Ergon network, the fault levels on the lower high voltages (11kV to 33kV) vary from 4kA to as high as 34kA.

Ergon has numerous types of high voltage cables in use around Queensland, but the most common types are XLPE and PLYS in single and multi-cored. The XLPE type of set sizes are now the common standard for new and replacement cables in the network. Figure 1.1 and Figure 1.2 displays a typical make up of an PLYS and XLPE cables.

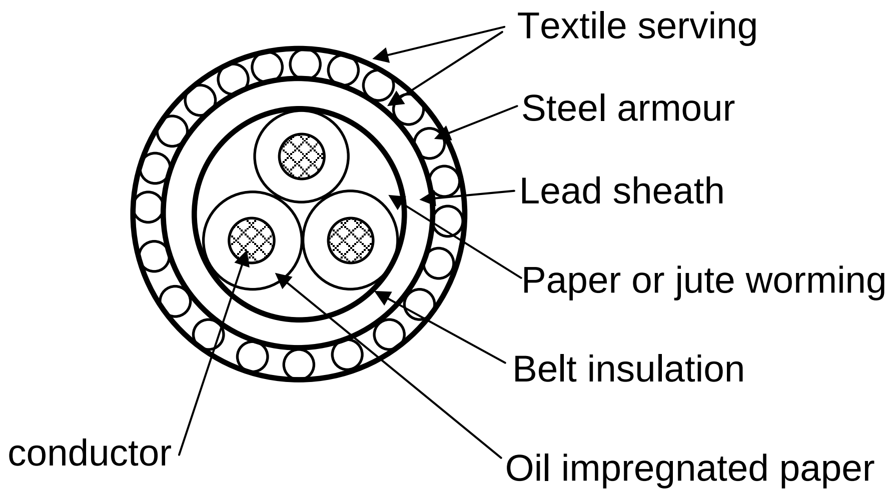


Figure 1.1 - Three core PLYS cable

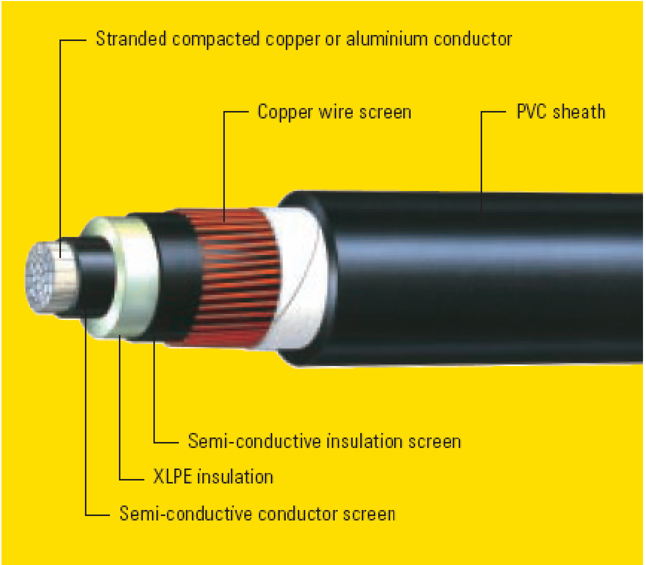


Figure 1.2 - Single Core XLPE Cable

(OLEX - Cables to IEC and Aust. Standards for Medium and High Voltage, P. 5)

In the past the ratings and capabilities of the transporting medium (lines and cables) have traditional been based on the manufacturers' datasheets. The move to the use of dynamic thermal ratings has emerged to allow the electricity asset owners to manage and expose their plant to a higher utilisation factor.

Dynamic thermal ratings are based on the environment the equipment is situated in and its exposure to the elements such as wind, moisture and temperature. The calculation of the ratings of cables is more difficult than aerial lines due to the thermal dissipation being hindered by the type of enclosure albeit direct buried, in conduits or ducts and the proximity of other heat dissipating equipment (other cables).

As with any conductor excessive heating may cause irreparable damage and the move to using thermal protection is one path to mitigate the risk of plant damage and the reduction of safety to the public.

The incident that occurred in early 1998 in Auckland, New Zealand is an example of the possible impact Ergon Energy could experience. The failures of the cables were attributed to the assumption made on the climatic conditions and installations of these cables. Once tests were carried out after the failures, it was confirmed that the cables had to be derated by almost half due to the soil conditions.

Chapter 2 - Literature Review

2.1. Power Cable History

The introduction of power cables was inevitable with the introduction of incandescent lighting, but cables capable for the use in high voltage networks first appeared in the 1885 when the City of Vienna installed cable for its 2kV network. This cable was insulated with rubber and protected by lead armour. This initial step paved the way forward for improvement and acceptance worldwide. A brief chronological list is presented below highlighting important events in high voltage cables.

- 1890 – Ferranti developed the first oil impregnated paper cable.
- 1891 – Ferranti's cable was installed in London for its 10kV network.
- 1917 – Oil filled cable principle developed by Emanueli.
- 1928 – Oil filled cable installed for use in the 66kV network in London.
- 1931 – Emanueli's cable used in the 132kV network in Chicago.
- 1932 – First oil filled pipe cable used in North America, the inventor was Benett.. This lead the path for other oil filled cable constructions.
- 1964 – XLPE made a strong impact for use as a medium high voltage cable.
- 1969 – Polyethylene cable used for 225kV network in France.
- 1980 – Flexible SF_6 filled high voltage cable designed for up to 362kV.

Since Ergon Energy's charter is to supply electricity as a DNSP, the cables employed by the company are nominally medium high voltage (11kV to 33kV), with minor lengths of 66/110/132 kV cable installations. The medium HV cables are usually paper lead alloy sheathed or cross-linked polyethylene.

2.2. Power Cable Standards

2.2.1. Australian Standards

Australian Standards (AS 1026-2004, AS 1429.1-2006, AS 1429.2-1998) define the mechanical composition requirements and the installation of cables. The maximum operating temperatures of the cables are also listed in these standards. These can be higher if specified by the cable supplier. These tables are listed in Appendix B - Standard Cable Data.

The AS/NZ standards do not deal with the cable ampacity. The calculation of ratings for cables is covered in the IEC standards that are dealt with next.

2.2.2. International Electrotechnical Commission Standards

As the Australian Standards does not delve into any current capacity ratings for cables, they do reference the IEC Standards 60287 and 60853 series for ratings of power cables. The 60287 series deal with the current capacity at 100 percent loading while the 60853 series cover the ratings required for cyclic and emergency use.

The IEC standards mentioned above break the ratings of cables into two voltage groups, for cables not greater than 36 kV and for those above 36 kV. These two voltage groups are separated by two categories, cyclic rating and emergency rating. Cyclic rating is based on a daily load curve where the load varies over a 24-hour period and each day is relatively the same. In emergency ratings, if the period is for greater than one hour then the use of the cyclic rating should be used else it is based on the load being between ten minutes and one hour.

To calculate the ratings at 100% loading the 60287 standards is made up of three parts. The first part IEC 60287.1, deals with the basic algorithms required to calculate the ampacity of the cable. This is at full load and takes into account the power losses that may be present during these loads. IEC 60287.2 encompasses the algorithms to determine the thermal resistance of the materials in the cable and the surrounding medium. The final part IEC 60287.3, comprises of a reference to ambient temperatures and thermal resistivity of soil in various countries. This part also provides an outline of the information required from the purchaser for the selection of the appropriate type of cable. This information if given to the manufacturer will ensure that the cable will be suitable for the type of operation it is required for and removes any assumptions the manufacturer must make.

Where the IEC (60287 and 60853 series) define the necessary rating algorithms but the implementation of this into real time varies with the situations presented, these include the thermal resistivity of the soil, which is largely dependant on the moisture migration or with differing soil compositions and their thermal characteristics. The makeup of power cables normally entails the use of a conductive protective sheath and IEEE Standard (575-1988) describe the methods for calculating induced voltages and methods for bonding these sheaths to ground.

2.2.3. Ergon Energy Standards

Ergon Energy via its *Network Planning Criteria Version 2.03*, initially select all works proposals based on using overhead constructions and then only varies this decision based on justifiable external factors. Some of the factors that may influence the use of cables are;

- Local Government conditions for subdivisions.
- Regional Business Areas as defined by individual Regions may be all undergrounded.
- Vegetation Management in environmentally sensitive areas.
- World Heritage areas.
- Cultural Heritage considerations.
- Flight paths associated with registered air strips.
- Local community expectations.
- Significant reliability improvement required.

- Contribution to costs by Third-Parties.

Ergon Energy uses standard industry tabulations and supplier manuals to rate underground cables. Currently where warranted in some situations a detailed investigation may be performed to determine actual cable ratings.

2.3. Thermal Issues

The aim of cable ratings is to maximise the permissible current flow through a cable to a given maximum operating temperature. The current flow causes the cable to heat and this in turn limits the loading capacity. Heating of cables is one of the major problems encountered with underground systems. There are generally two types of heat losses in a cable and these are current and voltage dependant losses. In this section, we will not deal with pipe-type cables, as Ergon Energy does not have any of these types in operation.

2.3.1. Heat Transfer

To calculate the current carrying capacity of cables, the rate of heat dissipation needs to be dealt with. The heat generated by the cable due to the losses (presented later in this chapter), need to be transferred away from the cable to ensure that the maximum operating temperature is not exceeded. Heat is transferred through the cable to the surrounding environment in several manners.

Cables that are installed underground, heat transfer is by conduction from the conductor to the other parts of the cable and finally to the surrounding medium. Convection and radiation or the most common found in cables exposed to air. As cables exposed to air have a higher rate of heat dissipation than those enclosed underground, the heat transfer may be expressed as per *Fourier's law*. The heat flux or transfer rate can be expressed as

$$q = -\frac{1}{\rho}\frac{d\theta}{dx} \quad \text{W/m}^2 \tag{2.1}$$

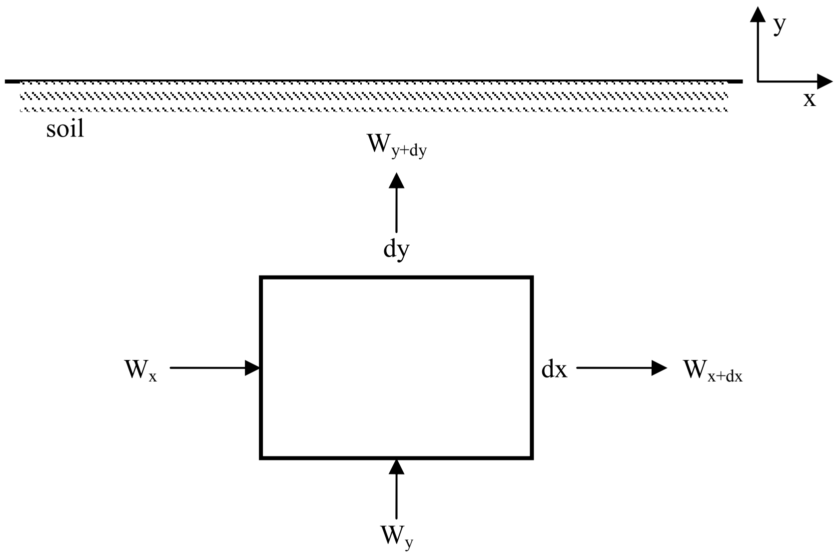


Figure 2.1 - Underground cable heat conduction

In reality, the length of the cable is far greater than its diameter and the end effects can be neglected. In Figure 2.1 above, we can apply *Fourier's Law* of heat conduction

$$W_x = -\frac{S}{\rho}\frac{\partial \theta}{\partial x} \quad \text{Watts} \tag{2.2}$$

where

W_x = heat transfer rate through area S in x direction (W)

ρ = thermal resistivity (K· m/W)

S = surface area perpendicular to heat flow (m^2)

$\frac{\partial \theta}{\partial x}$ = temperature gradient in x direction

This leads to the heat transfer across all surfaces perpendicular to x and y to be expressed as a *Taylor's* series expansion and neglecting the higher order terms gives the following equations.

$$\begin{aligned} W_{x+dx} &= W_x + \frac{\partial W_x}{\partial x}dx \\ W_{y+dy} &= W_y + \frac{\partial W_y}{\partial y}dy \end{aligned} \tag{2.3}$$

$$\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial \theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\rho}\frac{\partial \theta}{\partial y}\right)+W_{\text{int}}=c\frac{\partial \theta}{\partial t} \qquad (2.4)$$

2.3.2. Conductor Losses

Current flowing through a conductor will generate heat and the amount is often referred in joules, Watts per metre (W_c or W/m) or I^2R losses from the standard power calculations $W_c = I^2R$. This heat generated in the cable has to be dissipated into the surrounding soil or air. The resistance R should be kept to a minimum to reduce this heating effect. This resistance is mainly due to two factors, skin (y_s) and proximity (y_p) effects which is visualised in Figure 2.2 below. In most cases the manufacturer will provide the AC and DC resistances for varying configurations but we will show the alternate method of calculations should the AC resistance not be known.

$$R = R'\left(1 + y_s + y_p\right) \qquad (2.5)$$

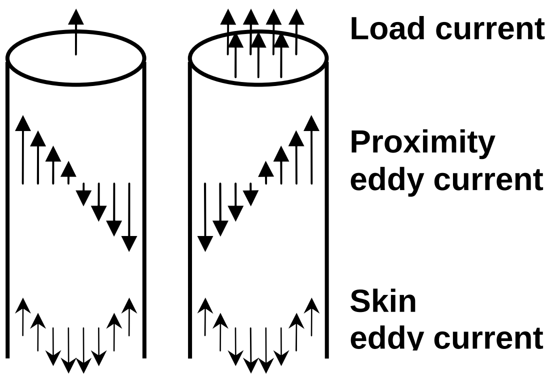


Figure 2.2 - Effects of skin and proximity phenomena

Skin Effects

The skin effect is a phenomena based on self inductance and the increased density of current carrying capacity to the outer edge of the conductor. This effect was investigated by people such as Maxwell and Heaviside. Generally at power frequencies, the ratio R/R' is close to unity and may be above unity for large diameter conductors which allow for the skin effect to be negligible for cables less than 150 mm^2, this is shown in the equations (2.6) and (2.7).

$$x^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \tag{2.6}$$

$$x_s^2 = x^2 k_s = \frac{8\pi f}{R'} \cdot 10^{-7} k_s \tag{2.7}$$

The skin effect factor is obtained using the values of k_s in **Table B.3**, which came from IEC 60287-1-1 page 63. In most cases the x_s is usually lower than 2.8 and the equation presented in (2.8) applies. The standards also mention alternative standard formulae to be used for tubular or hollow stranded conductor.

For $0 < x_s \leq 2.8$

$$y_s = \frac{x_s^4}{192 + 0.8x_s^2} \tag{2.8}$$

For $2.8 < x_s \leq 3.8$

$$y_s = -0.136 - 0.0177x_s + 0.0563x_s^2 \tag{2.9}$$

For $3.8 < x_s$

$$y_s = \frac{x_s}{2\sqrt{2}} - \frac{11}{15} \tag{2.10}$$

Proximity Effect

The "Proximity effect" is multiple conductors close together create mutual reactance into each other increasing the AC resistance of the cable. This is visualised as the current densities on the sides facing each are decreased and those on the opposite side are increased due to the differences in the densities of magnetic flux.

$$x_p^2 = x^2 k_p = \frac{8\pi f}{R'} \cdot 10^{-7} k_p \tag{2.11}$$

In the majority of cases the $x_p \leq 2.8$ and in the IEC 60287 where the configuration is a two-core or two single-core cables, the following approximation can be used.

$$y_p = 2.9ay \tag{2.12}$$

For three-core cables or three single-core cables,

$$y_p = ay^2\left(0.312y^2 + \frac{1.18}{a + 0.27}\right) \tag{2.13}$$

where

$$a = \frac{x_p^4}{192 + 0.8x_p^4} \qquad y = \frac{d_c}{s} \tag{2.14}$$

d_c is the diameter of conductor (mm);

s is the distance between conductor axes (mm).

For cables in flat formation, s is the spacing between adjacent phases. Where the spacing between adjacent phases is not equal, the distance will be taken as $s = \sqrt{s_1 \times s_2}$.

2.3.3. Dielectric Losses

The constituents of cables always include paper or other solid dielectric insulation. When these properties are subjected to alternating voltage, they behave as large capacitors with charging currents present. Each time the voltage is applied, the electrons in the material realign. This movement of the electrons causes friction that in turn creates heat. These losses are proportional to the capacitance, the phase voltage, the frequency and the loss factor (or power factor tan δ). For low to medium voltages these losses are generally small but increase rapidly for higher voltages.

The dielectric response of material is a consequence of its capacitive nature (ability to store charge) and its conductive nature (ability to pass charge). This material can be modelled by a resistor and capacitor in parallel.

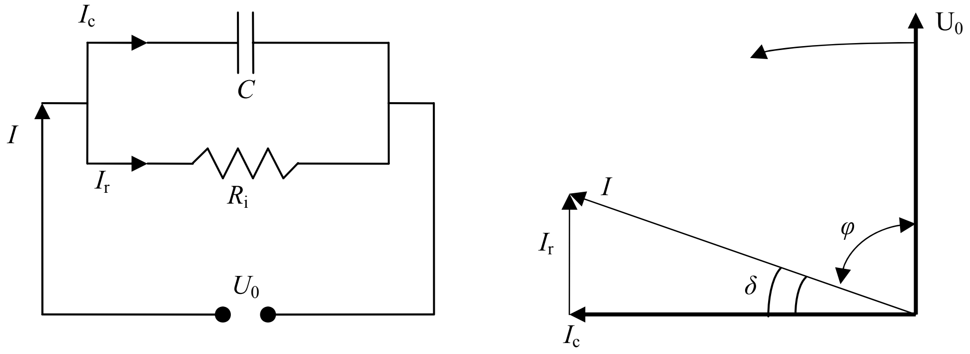


Figure 2.3 - Representation of cable insulation

To calculate the capacitance C the introduction of the relative permittivity of the dielectric ε is required and this is usually constant for each type of material. This is a ratio of the capacitance to the capacitance of the same material and size in a vacuum C_0.

$$\varepsilon = \frac{C}{C_0} \tag{2.15}$$

This leads to the standard calculation for circular insulation,

$$C = \varepsilon \cdot C_0 = \frac{\varepsilon}{18 \ln\left(\frac{D_i}{d_c}\right)} \cdot 10^{-9} \quad \text{F/m} \tag{2.16}$$

where

D_i = external diameter of the insulation in mm.

d_c = diameter of the conductor including screen if any in mm.

$$\tan\delta = \frac{|I_r|}{|I_c|} = \frac{U_0}{R_i C \omega U_0} = \frac{1}{R_i C \omega} \tag{2.17}$$

The equation for the dielectric loss per unit length in each phase is,

$$W_d = \frac{U_0^2}{R_i} = \omega C U_0^2 \tan\delta \quad \text{W/m} \tag{2.18}$$

Using Table B.5, dielectric losses need to be calculated for those insulation materials where the phase voltage is greater than or equal to the values given in the table. If the voltages are less than those indicated, then the dielectric loss may be ignored.

2.3.4. Sheath and Armour Losses

As the purpose of conductors is to carry current, this alternating current induces e.m.f.s in the cables metallic sheath that further reduces the current carrying ability. These losses are current dependant and under certain circumstances, large currents can flow in these coverings. These losses fall into two categories, circulating current ($\lambda_1^{'}$) and eddy current losses ($\lambda_1^{''}$).

The first is only found in single core cable systems where the sheaths are bonded together at two points usually at the ends of the cables. This sheath acts as a parallel conductor to the cable and the induced current flows along the sheath and returns via the sheath of other phases or via the earth. This can be reduced by increasing the sheath resistance and the three single-phase cables of a three-phase system are brought close together. This does however introduce increased eddy currents and mutual heating of the cables.

$$\lambda_1 = \lambda_1^{'} + \lambda_1^{''} \tag{2.19}$$

The loss due to eddy currents is as mentioned previously, circulate radially by the skin effect and azimuthally by the proximity effect (Anders 1997). This reaches a maximum when the single-phase conductors of the three-phase system are situated as close together as possible. This can also be reduced by increasing the sheath resistance and the ratio of cable spacing to the sheath. In many cases, this loss is small compared to the circulating losses and can be ignored (Anders 1997).

Metallic armour incur losses the same as for the sheaths in relation to circulating ($\lambda_2^{'}$) and eddy currents ($\lambda_2^{''}$) flowing. Since armour has magnetic properties, a further loss occurs which is caused by hysteresis. Again, this is due to the amount of magnetic fields produced from its own conductor or other in close proximity. These combined magnetic fields can cause significant hysteresis losses (Wijeratna et al).

$$\lambda_2 = \lambda_2^{'} + \lambda_2^{''} \tag{2.20}$$

Those cables that have nonmagnetic armour, the usual practice is to take the combined sheath and armour resistance as a whole, and calculate the loss as sheath loss.

The IEEE Standard 575 introduces guidelines into the calculation of induction in cable sheaths and recommends various methods of sheath bonding. The most common types of bonding are single point, double or multiple points and cross bonding.

The single and multi-point bonding have some advantages and disadvantages. Since one end is not connected directly to ground, this breaks the possible circulating currents, but the open end, especially on long cables may have potentially high voltage rise on the sheaths. This can be overcome by use of sheath voltage limiters. In single point bonding for a line to ground fault, the current must return via the earth. For multi-bonding, the ground fault currents will return via the cable sheaths. Of course, the main disadvantage to these types of bonding is the reduced current carrying capacity of the cables. Cross bonding has similar properties to multi-bonding except for the almost nonexistent induction for parallel lines. Ergon Energy employs the double bonding method in its cable installations and this will be focus.

Since we deal with three-phase systems the loss factors λ_1 can be calculated for the two standard laying formations of trefoil (Figure 2.4 a) and flat (Figure 2.4 b & c). In both cases the $\lambda_1^{''}$=0.

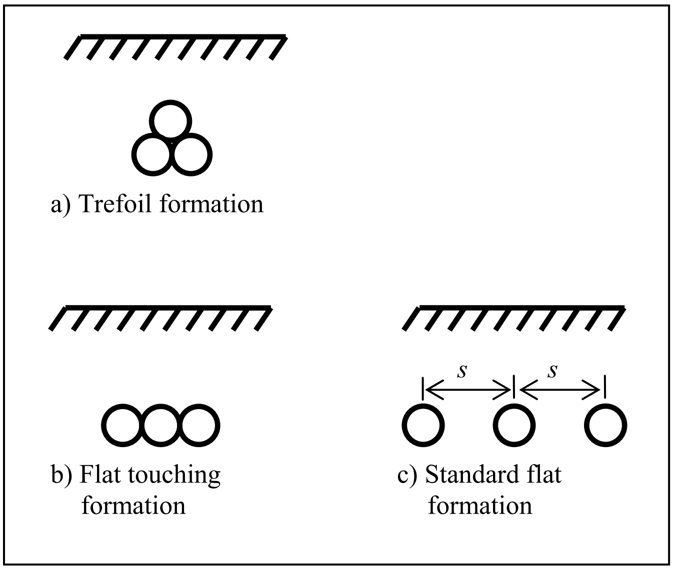


Figure 2.4 - Standard cable layout formation

For three single-core cables in trefoil formation and bonded at both ends,

$$\lambda_1' = \frac{R_s}{R} \cdot \frac{1}{1 + \left(\frac{R_s}{X}\right)^2} \tag{2.21}$$

where X is the reactance per unit length of sheath or screen given by;

$$X = 2\omega \cdot 10^{-7} \cdot \ln\left(\frac{2s}{d}\right) \ \Omega/\text{m}$$

For three single-core cables in flat formation and bonded at both ends,

$$\lambda_1' = \frac{R_s}{R} \cdot \frac{1}{1 + \left(\frac{R_s}{X_1}\right)^2} \tag{2.22}$$

where X_1 is the reactance per unit length of sheath or screen given by;

$$X_1 = 2\omega \cdot 10^{-7} \cdot \ln\left\{2 \cdot \sqrt[3]{2} \cdot \left(\frac{s}{d}\right)\right\} \ \Omega/\text{m} \tag{2.23}$$

The formulae cited above are identical to those in the IEC standards and have been widely accepted by the engineering profession throughout the world.

2.4. Thermal Analogue Model Method

2.4.1. Thermal Resistance

Materials that impede heat flow away from the cable is due to its thermal resistance. Even metallic components have a small amount of resistance but is negligible in any calculations required. An analogy between electrical resistance and thermal resistance may be associated with the driving force to a corresponding transfer rate of electricity or heat.

The formula for thermal resistance of a cylindrical layer per unit length is

$$T = \frac{\rho_{th}}{2\pi} \ln \frac{r_2}{r_1} \tag{2.24}$$

For a rectangular wall

$$T = \rho_{th} \frac{l}{S} \tag{2.25}$$

This is similar to *Ohm's Law*

$$R = \frac{V_1 - V_2}{I} = \rho_{el} \frac{l}{S} \tag{2.26}$$

Which gives way to a thermal equivalent to *Ohm's Law*

$$\begin{aligned} W &= \frac{\Delta\theta}{T} \\ &= \frac{\theta_1 - \theta_{\mathrm{amb}}}{T_{\mathrm{tot}}} \end{aligned} \tag{2.27}$$

Equation (2.27) gives total heat transfer rate from the overall temperature difference from conductor to air and the total thermal resistance T_{tot}. This equivalent circuit can be used for a cable as shown in Figure 2.5 below.

As conduction and convection resistances are in series then they may be added up to give

$$T_{\text{tot}} = \frac{\rho_A}{2\pi}\ln\frac{r_2}{r_1} + \frac{\rho_B}{2\pi}\ln\frac{r_3}{r_2} + \frac{\rho_C}{2\pi}\ln\frac{r_4}{r_3} + \frac{1}{2\pi r_4 h} \tag{2.28}$$

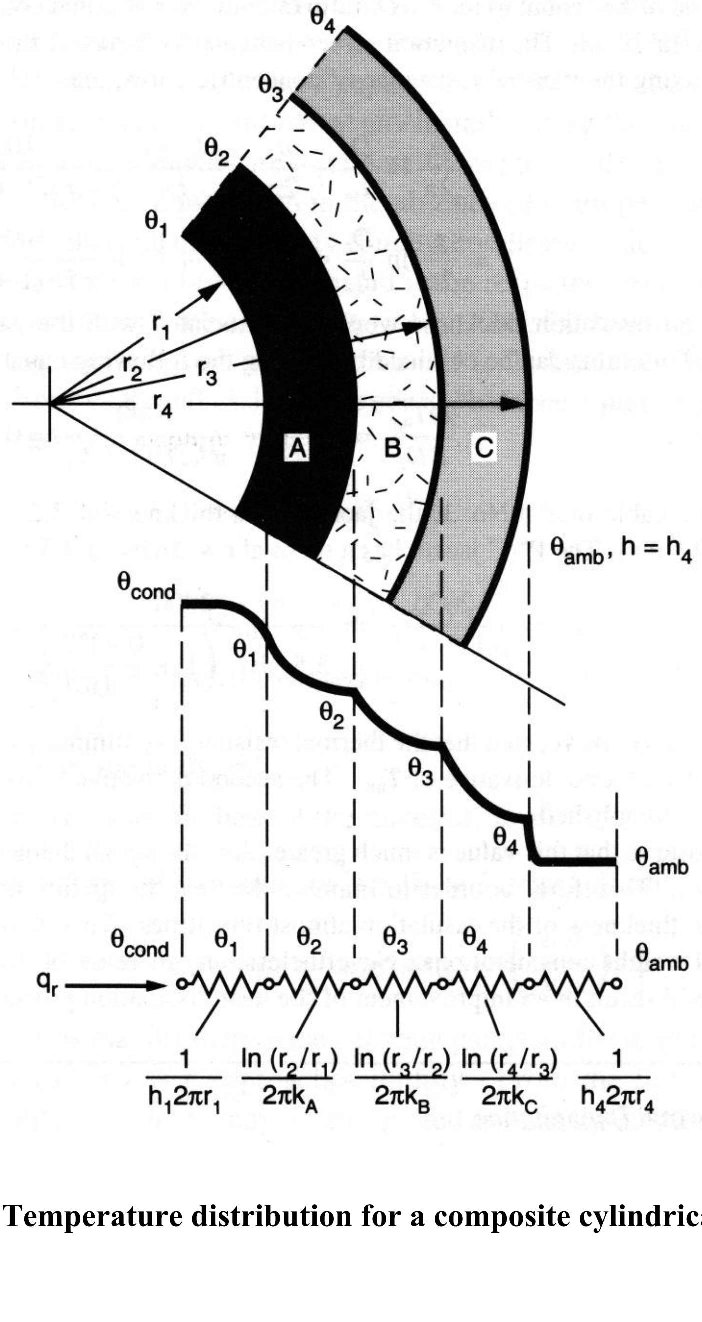


Figure 2.5 - Temperature distribution for a composite cylindrical wall

2.4.2. Thermal Capacitance

As mentioned previously, many cable-rating issues are time dependant. This is typical where two circuits are sharing equal load and suddenly one of the circuits switches off. The load increase on the cable in service causes a slow change in the increase in temperature distribution within the cable and the surrounding environment.

As Anders (1997, p 39) describes, "The thermal capacity of the insulation is not a linear function of the thickness of the dielectric. To improve the accuracy of the approximate solution using lumped constants, Van Wormer, in 1955, proposed a simple method of allocating the thermal capacitance between the conductor and the sheath so that the total heat stored in the insulation is represented."

Since the thermal properties are directly involved with resistance and capacitance, correlation between electrical and thermal networks exists.

$$\begin{aligned} \text{Electrical:} \quad \Delta V &= \frac{Q}{C} \\ \text{Thermal:} \quad \Delta \theta &= \frac{W_{th}}{Q_{th}} \end{aligned} \tag{2.29}$$

The thermal capacitance is given by

$$Q_{th} = Vc \tag{2.30}$$

$$Q_{th} = \frac{\pi}{4}\left(D_2^2 - D_1^2\right)c \tag{2.31}$$

where

V = Volume (m^3)

c = Specific heat (J/(m^3·K))

D_1 = internal diameter (m)

D_2 = external diameter (m)

Dielectric losses are the main concern when dealing with thermal capacitance.

2.4.3. Van Wormer Coefficient

As mentioned in 2.4.2, an approximate solution can be obtained by creating lumped thermal constants. Van Wormer created a ladder network representation of a cable and its surroundings for both short and long-term transients. Short term transients are accepted globally as to the duration of the transition not to be greater than ⅓ $\Sigma T \cdot \Sigma Q$, which usually last anywhere between ten minutes to about one hour. These will be of interest when looking at emergency ratings.

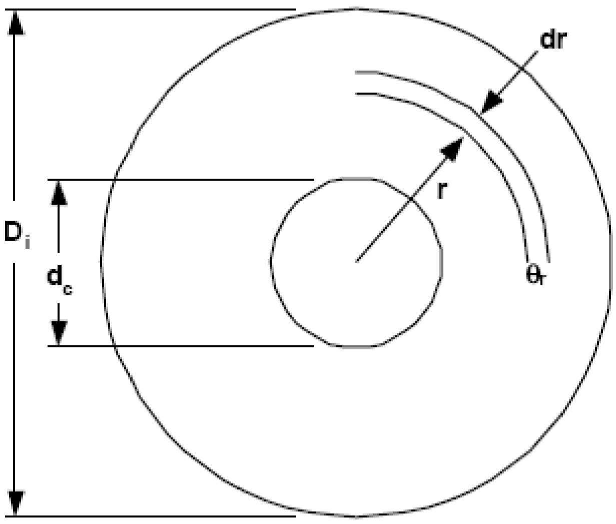


Figure 2.6 - Temperature distribution with a cable

The distribution factor p can be calculated as

$$p = \frac{1}{2\ln\left(\frac{D_i}{d_c}\right)} - \frac{1}{\left(\frac{D_i}{Ds}\right)^2 - 1} \tag{2.32}$$

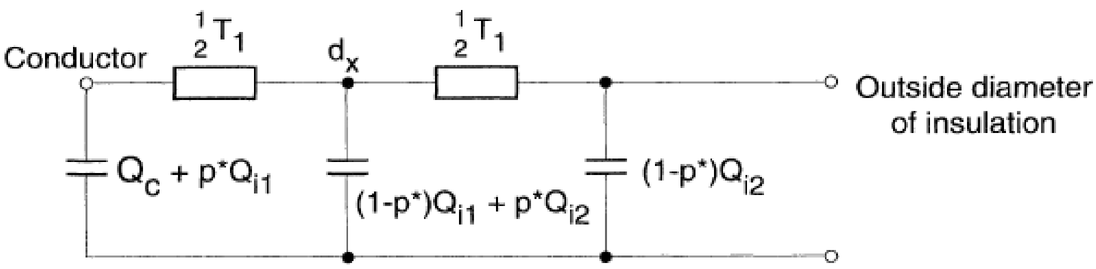


Figure 2.7 - Short term transient representation

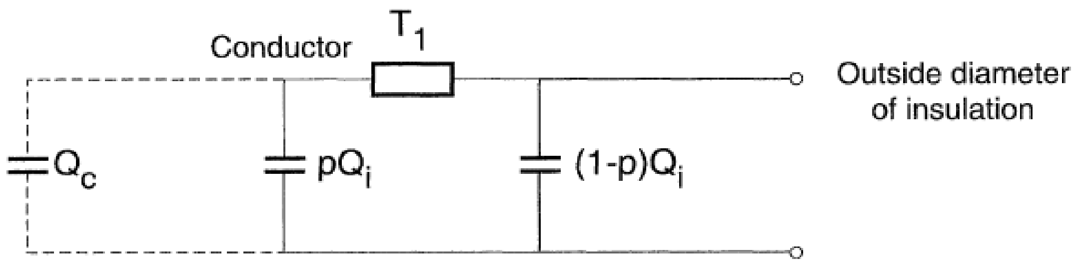


Figure 2.8 - Long term transient representation

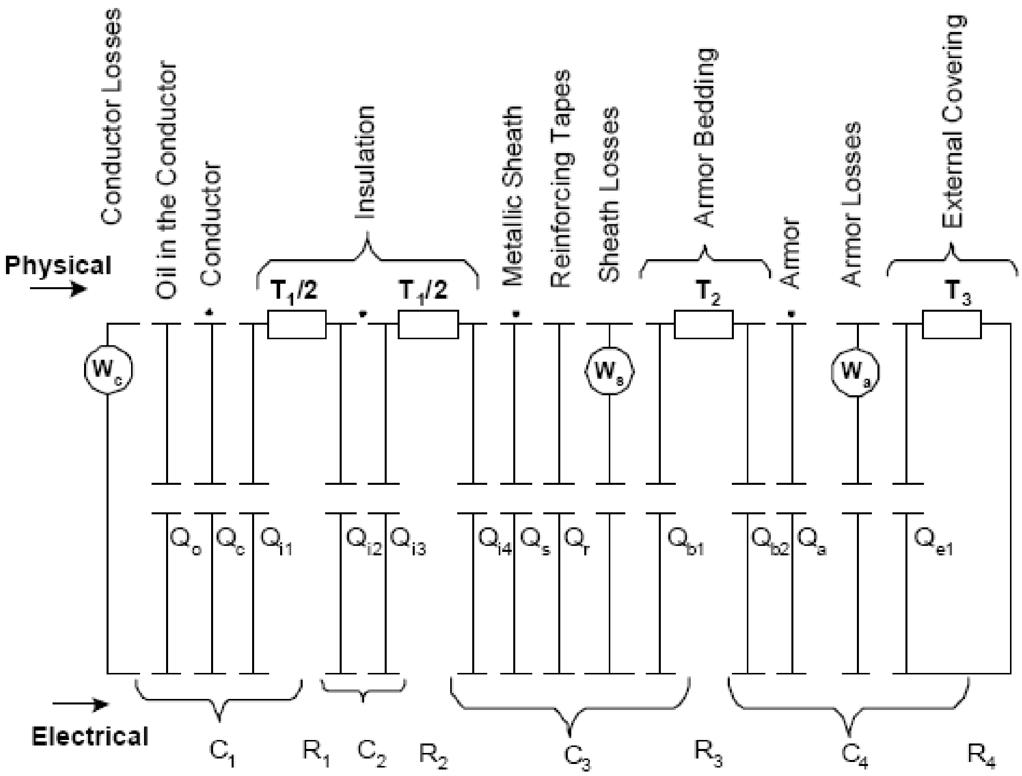


Figure 2.9 – A typical thermal network model of a cable

2.5. Numerical Model Methods

As seen previously, the classic analytical methods used are subject to assumptions that have to be made. Numerical methods such as finite element, finite difference and boundary elements can overcome certain limitations that the classical methods cannot solve accurately. The iterative approach is used to calculate the ampacity of the cables. The iterative method is by specifying a certain conductor current and calculating the corresponding conductor temperature. The current is adjusted and the calculation repeated until the specified temperature is found convergent within a specified tolerance (maximum operating temperature).

In the calculations previously, separate computations are required for the internal and external parts of the cable. An assumption was made that the heat flow into the soil is proportional to the attainment factor of the transient between the conductor and the outer surface of the cable (IEC 62095). The addition of the capability of a numerical method is that in cases where the other cables are actually touching, the analytical method treated each cable separately and summated the heat flows. In finite element and difference methods, the temperature rise caused by simultaneous operation of all cables is considered. A direct solution of the heat conduction equation employing the finite element method offers such a possibility.

Each method has its issues. Some difficulties may arise when using finite element method as it does not handle well in modeling long thin objects, such as cables, in three dimensions. The finite difference method is suitable for modelling three dimensional cable problems. This method is intended for use with rectangular elements and hence is not well suited for modelling curved surfaces. The other method mentioned being the boundary elements method requires less data input and computational processes but is not suited for transient analysis.

2.5.1. Finite Element Method

The IEC standard 62095 for numerical methods deals with the finite element method. This method is used to solve partial differential equations that culminate to form the heat transfer of cables. ‘The fundamental concept of the finite element method is that temperature can be approximated by a discrete model composed of a set of continuous functions defined over a finite number of sub-domains. The piecewise continuous functions are defined using the values of temperature at a finite number of points in the region of interest’ (IEC 62095, p15).

The discrete solution using finite element method is constructed as follows.

a) A finite number of points in the solution region is identified. These points are called nodal points or nodes.

b) The value of the temperature at each node is denoted as variable which is to be determined.

c) The region of interest is divided into a finite number of sub-regions called elements. These elements are connected at common nodal points and collectively approximate the shape of the region.

d) Temperature is approximated over each element by a polynomial that is defined using nodal values of the temperature. A different polynomial is defined for each element, but the element polynomials are selected in such a way that continuity is maintained along the element boundaries. The nodal values are computed so that they provide the "best" approximation possible to the true temperature distribution. This approach results in a matrix equation whose solution vector contains coefficients of the approximating polynomials. The solution vector of the algebraic equations gives the required nodal temperatures. The answer is then known throughout the solution region.

In solutions for cable ratings, the model is usually in two dimensional plane of x and y and are generally either triangular or quadrilateral in shape. The element function becomes a plane (Figure 2.10) or a curved surface (Figure 2.11). The plane is associated with the minimum number of element nodes, which is three for the triangle and four for the quadrilateral.

The accuracy of the calculations will be dependant on the user’s control over several parameters. These are the size of the region to be discretised, the size of the elements constructed by mesh generator, the type and location of region boundaries, the representation of cable losses, and the selection of the time step in transient analysis.

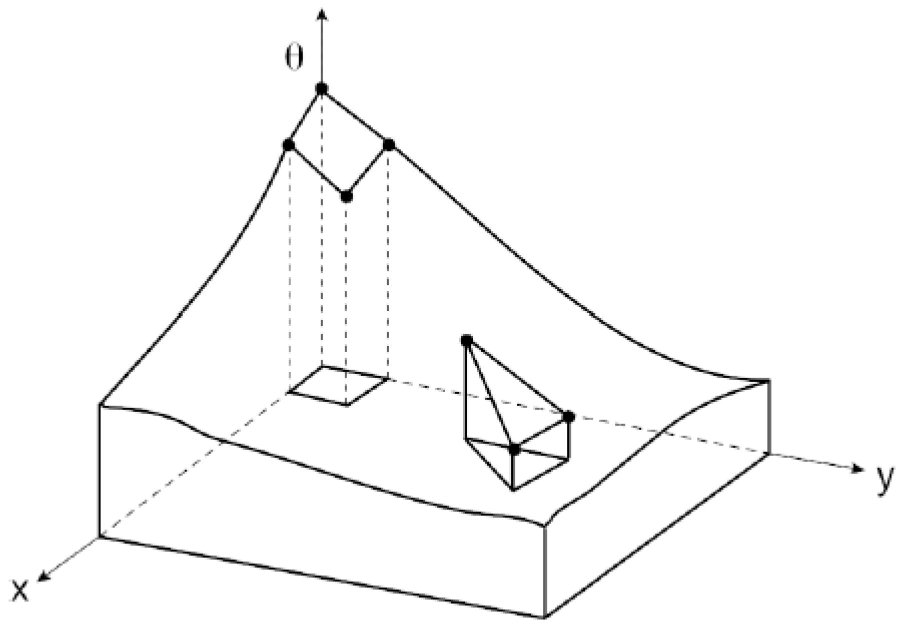


Figure 2.10 - Triangular or quadrilateral elements
(IEC 62095, p.23)

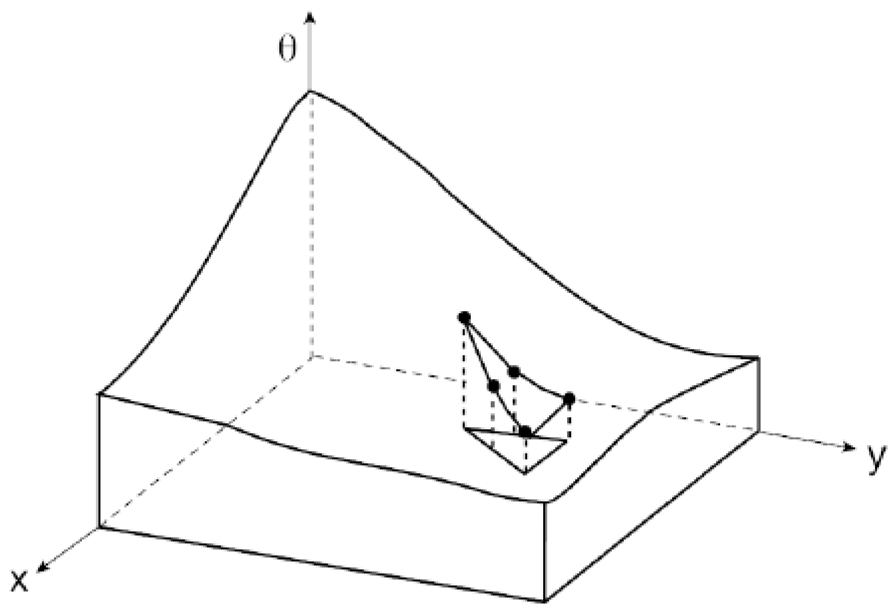


Figure 2.11 – Quadratic-triangular element
(IEC 62095, p.23)

Size of the Region

Boundary locations is an important consideration. The objective is to select a region large enough so that the calculated values along these boundaries concur with those in the physical world. The earth's surface is one such boundary but the bottom and sides need to be defined in such a way that the nodal temperatures all have the same value and that the temperature gradient across the boundary is equal to zero.

'Experience plus a study of how others modelled similar infinite regions is probably the best guide. In our experience, a rectangular field 10 m wide and 5 m deep, with the cables located in the centre, gives satisfactory results in the majority of practical cases' (IEC 62095, p 25).

The radius of the soil out to which the heat dissipates will increase with time in transient analysis. Practically it is sufficient to consider the radius that a sensible temperature rise will occur. This can calculated by

$$\theta_{r,t} = \frac{W_I \rho_s}{4\pi}\left[-Ei\left(\frac{-r^2}{4\delta t}\right)\right] \tag{2.33}$$

where $\theta_{r,t}$ is the threshold temperature value at the distance r from the cable axis. This value can be taken as 0.1 K when the number of cables is not greater than 3 and suitably smaller for a large number of cables (Anders, 1997).

Element Size

By specifying the size of the space between boundary nodes for the various parts of the network being analyzed (cables, backfill, soil etc.), the user retains some control. The element sizes should be the smallest near the cable to obtain accurate results. The use of different element sizes and the detail are shown below in Figure 2.12.

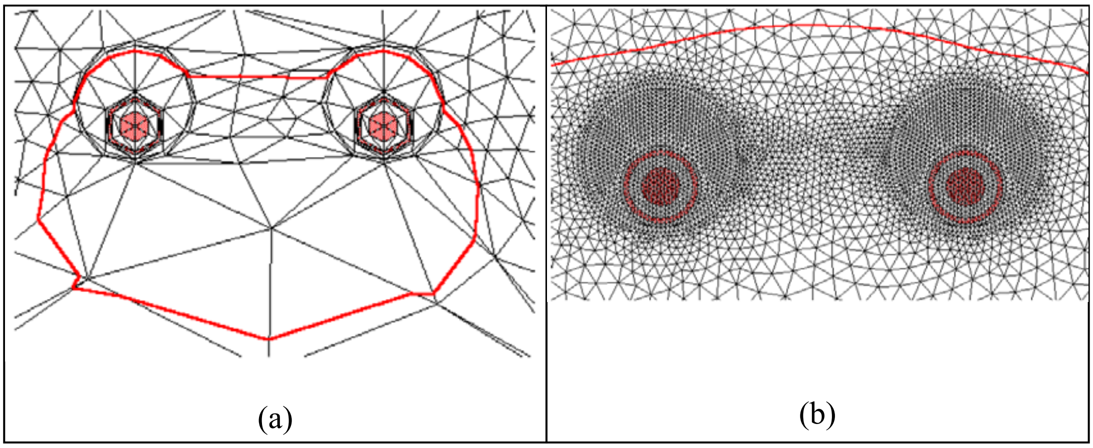


Figure 2.12 - Using different element sizes

Boundary Conditions

The finite element method allows for the representations of different boundary conditions and random boundary locations, these include straight line and curved boundary representations. For current ratings, three different boundary conditions are relevant. Isothermal condition exists if the temperature is known along a section of the boundary. This temperature may be a function of the surface length. If the conditions in IEC 60287 are to be modelled then this temperature is the ambient temperature at the depth of the buried cable.

A convection boundary exists if heat is gained or lost, and should be used when large diameter cables are installed close to the ground surface. If this is the case then the user must specify the heat convection coefficient and air ambient temperature. This coefficient ranges from 2 to 25 W/m^2·K for free convection and 25 to 250 W/m^2·K.

The third type of condition is the constant heat flux boundary condition. This is usually required when there are other heat sources in the vicinity of the cables under examination.

Representation of Cable Losses

The cable losses mentioned previously, conductor, sheath and dielectric are denoted as heat sources in the numerical method. These losses require to be varied with time and / or temperature. Using the methods for calculation in the analytical method, the values for losses need to be calculated at each step using an iterative procedure.

Selection of Time Step

As computations in the finite element method require evaluation of temperatures in increments of time, the size of the time step is crucial for the accuracy of the computations.

The duration of the time step, $\Delta\tau$, will depend on

a) the time constant, $\Sigma T \bullet \Sigma Q$ of the network (defined as the product of its total thermal resistance (between conductor and outer surface) and its total thermal capacitance (whole cable)),

b) time elapsed from the beginning of the transient, τ, and

c) the location of the time τ, with relation to the shape of the load curve being applied.

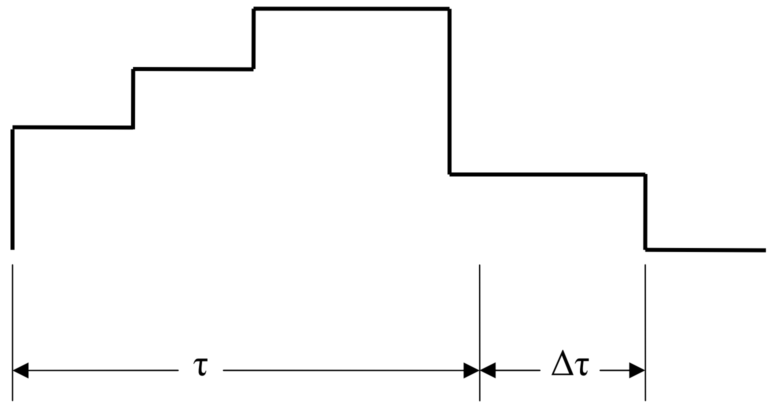


Figure 2.13 - The time step, the load curve and the time elapsed

These conditions are suggested for the selection of the time step $\Delta\tau$ (CIGRE, 1983),

$$\begin{aligned}
\log_{10}\frac{\Delta\tau}{\Sigma T\cdot\Sigma Q} &= \frac{1}{3}\log_{10}\frac{\tau}{\Sigma T\cdot\Sigma Q} - 1.58 \qquad \text{for} \qquad \tau < \frac{1}{3}\Sigma T\cdot\Sigma Q \\
\log_{10}\frac{\Delta\tau}{\Sigma T\cdot\Sigma Q} &= \frac{1}{3}\log_{10}\frac{\tau}{\Sigma T\cdot\Sigma Q} - 1.25 \qquad \text{for} \qquad \tau > \frac{1}{3}\Sigma T\cdot\Sigma Q
\end{aligned} \tag{2.34}$$

2.6. Commercial Software Packages

Both packages available to Ergon Energy are CYMECAP (http://www.cyme.com/software/cymcap/) and SIROLEX (http://www.olex.com/). Both of these packages use the finite element methods utilising both the Neher - McGrath and IEC 60287 methods. I have only been able to find two other package that deals specifically with power systems and both were American companies, that is USAmp (http://www.usi-power.com/Products&Services/USAmp/USAmp.html) and Ampcalc (http://www.calcware.com/index.html). This program only utilises the Neher-McGrath method, which is expected as most American ratings are based on this. I expect that there are others including a substantial amount of in-house programs that companies would have developed to assist in the ratings debate.

All of these packages use a graphical user interface that operates in a Microsoft Windows environment. As I do not have access to these programs, I could review little in regards to the actual operation of the software.

2.7. Distributed Temperature Sensing

The emergence in the use of DTS for real time temperature monitoring of cables has introduced a more accurate method of enabling cables to be utilised to a maximum, determination of hot spots and prediction of the life span of cables. Before DTS, the measuring of real time temperatures on cables was with Thermocouples and thermisters to provide localised temperature measurement. These devices are inexpensive, and have good reliability and accuracy. They did have limitations, they only measure temperature at a single location and as a result of these discrete measurements, “hot spots” may be missed.

The use of DTS is detailed in various papers including the *Electricity Engineers’ Association Annual Conference, Auckland, New Zealand 2000*. This paper details the hardware, software and applications by some electricity companies in Australia.

The DTS philosophy is relatively simple. Using pulses of laser light and analysing the Raman/Stokes backscatter produced is dependant on the reflection of certain intensities of frequencies (dependant on temperature) and the time delay in the reflection (distance along the cable). The main backscatter from the laser pulse is in the Rayleigh Band, which is the same wavelength as the light pulse that was launched and is the strongest signal returned. The weakest of the backscatter waves are those that have been disturbed by atomic and molecular vibrations (heating).

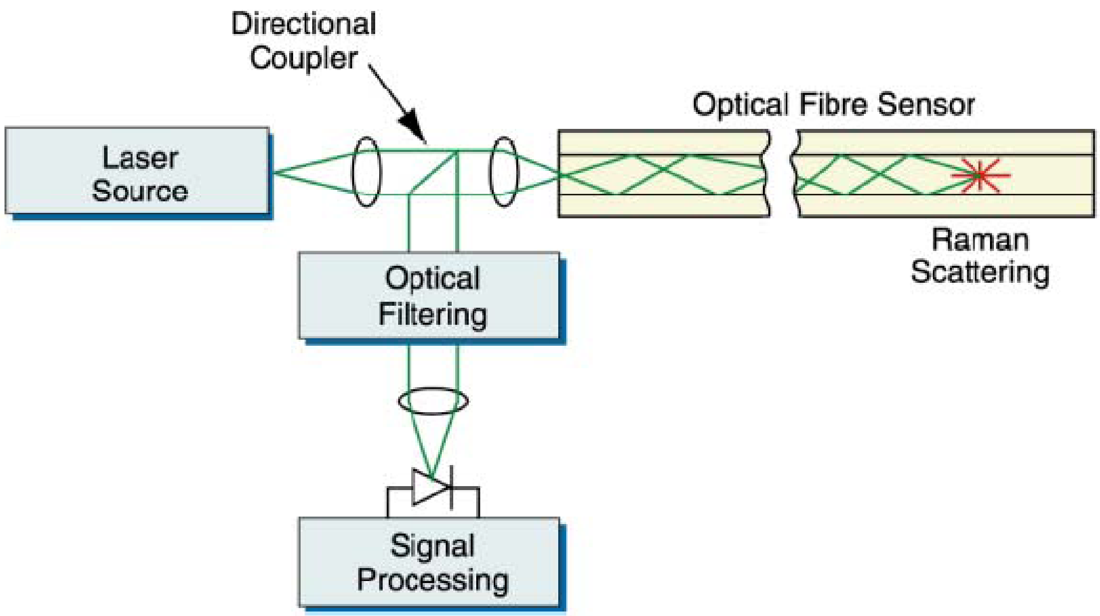


Figure 2.14 - Optical Time Domain Reflectometry

The Stokes / Raman signal is used for the evaluation of temperature. It has unique temperature dependence and it is sufficiently strong enough to be measured. Its wavelength is shifted approximately 40nm from the main band (Rayleigh). This allows the dominant Rayleigh and Brillouin bands to be filtered out.

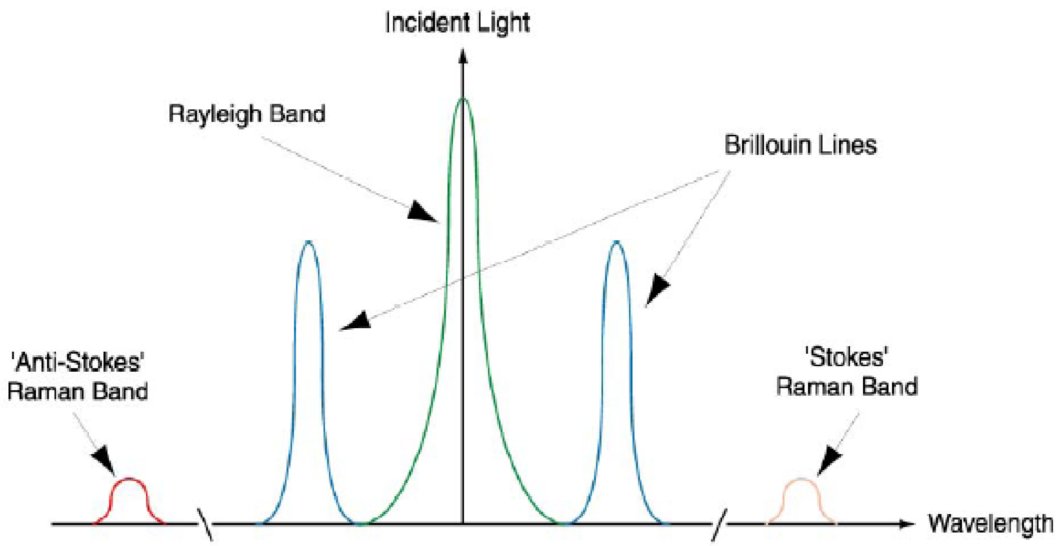


Figure 2.15 - Backscatter spectrum (Brown, 2003)

The ‘Stokes’ band (upper band) is stable and has little temperature sensitivity. The lower band or ‘Anti-Stokes’ band has sensitivity to temperature and higher the energy in the band means greater the temperature. Accuracy within 1 degree and 1 metre is achievable with this technology.

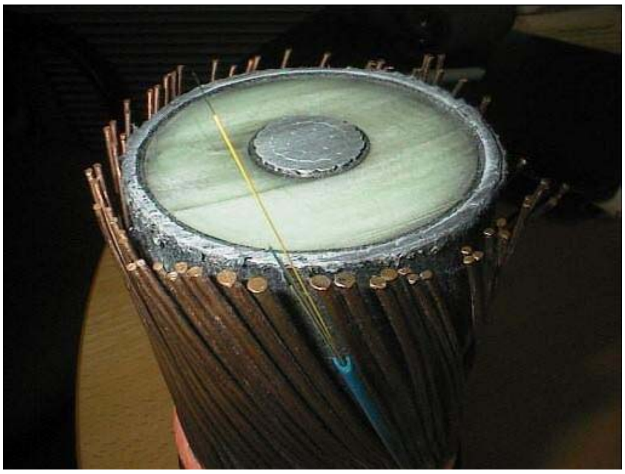


Figure 2.16 - Fibre optic incorporated with the cable (Peck et al. 2000)

After a substantial amount of discussions with our Asset Manager Group and our group, System Operations, we have convinced Ergon to proceed with DTS. The cost of having the fibre optic included with the supply of the cable is minimal approximately two dollars per metre; Ergon has now included this in their standard cable contracts from suppliers. The fibre optic can be included in the manufacture of the cable or laid externally with the cable.

Figure 2.17 - Fibre optic laid beside cables (Peck et al., 2000)

2.8. Protection Relays Currently in Use

Ergon Energy has a diverse selection of protection relays that it uses in the distribution network, and they fall into two categories, electromechanical and solid state. Since the inauguration of Ergon Energy from six Queensland regional electricity boards into one, the move for standardisation of equipment is well underway.

The type of protection relay and its requirements are revised every two years and a contract is awarded to a preferred supplier. Earlier this year the Schweitzer Company is the main supplier to Ergon for the SEL model relays (Figure D.3). The previous contractor was Alstom with the Micom series relay (Figure D.4). Should the supplier not be able to accommodate any requests of certain functionalities in the relay from Ergon, the relay may be purchased from an alternate source.

For this area, the relays being used are nominally called feeder management relays, a single relay with multi-function purposes. These relays use solid-state devices and programmable logic to perform varying protection functions such as overcurrent (including directional), high impedance ground faults, under and over frequency and voltage. It can also handle synchronising checks; perform programmable auto reclosing, and detection of phase sequencing and unbalance issues. The relays of today also incorporate fault location and metering capabilities.

At the time of undertaking the project, it was thought that the SEL relay could be programmed for thermal protection. This was not the case as the only relays that have thermal functionality are the SEL 701 Monitor relays. However it was found that the Micom P14x relay includes a thermal overload feature.

The overload feature provides both an alarm and trip stage. The logic is based on the thermal element capable of being set by a single or dual time constant equation as shown below (Asltom 2004).

Single time constant:

$$t = \tau_1 \ln\left(\frac{I^2 - (1.05 \cdot I_{\mathrm{TH}})^2}{I^2 - I_{\mathrm{p}}^{\ 2}}\right) \tag{2.35}$$

Dual time constant:

$$0.4e^{-t/\tau_1} + 0.6e^{-t/\tau_1} = \left(\frac{I^2 - (1.05 \cdot I_{\mathrm{TH}})^2}{I^2 - I_{\mathrm{p}}^{\ 2}}\right) \tag{2.36}$$

where

I is the overload current

I_{p} is the pre-fault steady state load

t is the time to trip

I_{TH} is the thermal trip level

Chapter 3 - Methodology

3.1. Preliminary Tasks

3.1.1. Technical Research

To implement any methods into a project there is a requirement to ensure that the problem at hand is understood. The main section of the research required knowledge on the effects and issues with power cables and their current rating capability. This was accomplished by the reviewing the existing Australian and IEC standards, the Ergon Network Planning and Security Criteria and other relevant written material. Most of this material was dealt with in the previous chapter. The assistance of some of our experience staff will also be sort.

3.1.2. Cable Site Selection

At the time of planning the research project, Ergon Energy decided to trial some Resistive Temperature Detectors (RTD) in the system. These were to be located at a substation where SCADA already exists and the temperature could be stored on the SCADA logging system.

The Garbutt substation, located in Townsville was an ideal choice as the soil in and around the area was said to have a high soil resistivity level. Further reasoning for choice of site, is that additional cables need to be installed for system augmentation. It also required some of the existing cable exits at the substation to be uncovered and moved during the process of works.

3.2. Data Gathering

The required data needed to be, the current of the cables, the temperature of the cable, the ground temperature and air temperature. It was vital that these records could be stored with a corresponding timestamp to ensure correlation of the data was correct.

As this information was encompassed into the SCADA system, the ability to store the information regularly was not an issue. The retrieval process was somewhat if a different story. The temporary logging system used required special software by Wonderware called "Activefactory" to be installed on my computer. Once the software was installed, an interface connection is established and downloading of data into MS Excel spreadsheets is possible.

3.2.1. Distribution Feeder Cables Temperatures

Since all the exit cables were uncovered, it was decided that RTDs be installed on all of the exit cables. A drawing detailing the location of the detectors is shown in Figure C.2. Some issues did occur with the installation and will be reviewed latter in section 4.1.

It is important that at least a couple of cables be analysed especially with the different composition of cables. The two common types that are installed at this substation are the XLPE single-core 400 mm^2 copper and the XLPE three-core (triplex) 240mm^2 copper. The single core cable circuits are laid in the ground in trefoil formation (Figure 2.4a).

3.2.2. Distribution Feeder Daily Load Curves

To enable further analysis into the heating effects and the relationship of temperature to the currents flowing in the cables, the collation of feeder currents is required. This also allows to view any possible correlation of the heat dissipation relative to the time of the day, the loads etc. As this data is historically logged, it should not be any concern in the availability for use.

Most of the feeders out of Garbutt Substation have varying loads; some are daytime industrial, residential loads while others tend to be at a reasonable constant load. This will have an impact on the heating factors that occur and the stress the cables may be subjected to especially in emergencies.

3.3. Model Development

The critical section of the project is to try to establish the relationship between the cable and factors that affect the heat dissipation. These factors such as soil thermal resistance, the components of the cables, the load and the climate, need to be evaluated. Using the research found on the subject and the data available a model can be constructed. To enable this phase to fruit, certain analytical processes need to be constructed.

3.3.1. Thermal Analogue Model

After researching the issues surrounding the effects of heat and its dissipation away from the cable, it was initially decided to concentrate on one type of cable. If time permits then attempt to modify it to suit other cable types with little or no modification.

As mentioned in previously, the main concern with cables is the heat generated (normally in Watts or Joules) and the rate of dissipation from the cable. The total power loss in a cable is the algebraic sum of the individual losses that occur due to the varying components of the cable and the effect of EMF. These losses consist of the conductor loss (W_c), sheath loss (W_s) and armour loss (W_a).

$$W_t = W_c + W_s + W_a = W_c\left(1 + \lambda_1 + \lambda_2\right) \tag{3.1}$$

As the sheath and armour loss are both a ratio of their losses to the loss due from the conductor, they are termed loss factors λ_1 and λ_2 respectively. These affect the cable differently under two types of conditions, steady-state and transient.

3.3.2. Steady State Conditions

Steady state conditions are when the current flow through the cable is at a constant value and the temperature of the cable is constant i.e. the heat generated is equal to the heat dissipated. The temperature value used is dependant on the type of cable but in this model we will be looking at XLPE construction where the maximum temperature normally allowed for steady-state is 90^0 C (Table B.2).

Using equation (2.27) an equivalent ladder circuit can be constructed. Since the XLPE cable used in both single and three-core cable do not have a lead sheath but a screen, the loss T_2 is not required.

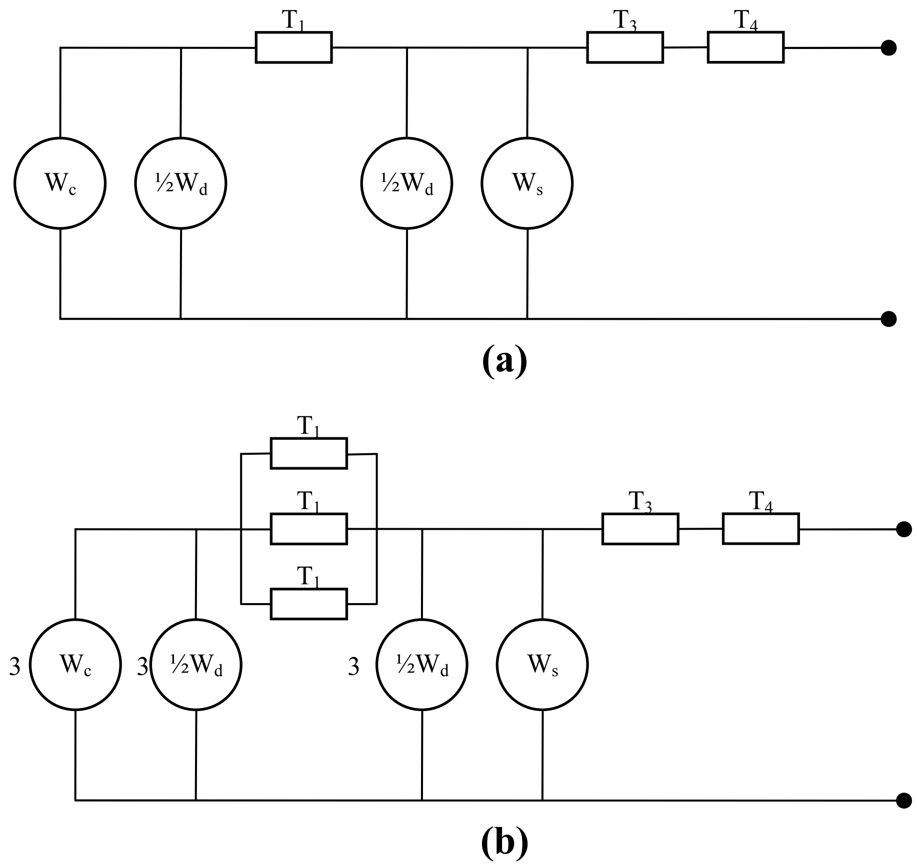


Figure 3.1 - Ladder diagram steady-state for XLPE cables
(a) Single core (b) 3 core XLPE cables

Using the above ladder network for XLPE the expression for the difference of temperature between the conductor and the surrounding medium is created.

$$\Delta\theta = \left(W_c + \frac{1}{2}W_d\right)T_1 + \left[W_c\left(1+\lambda_1+\lambda_2\right)+W_d\right]n\left(T_3+T_4\right) \qquad (3.2)$$

Since the lossees in the conductor are relative to the current it carries, $W_c = I^2R$ gives the formula for calculating the steady-state current.

$$I = \left[\frac{\Delta\theta - W_d\left[0.5T_1 + n(T_3 + T_4)\right]}{RT_1 + nR(1 + \lambda_1 + \lambda_2)(T_3 + T_4)} \right]^{0.5} \tag{3.3}$$

To determine the current required for steady-state conditions, certain quantities are required for the calculation. The following steps may be required depending on the information given by the manufacturer.

1. Calculate the DC resistance *R'* of the conductor at the maximum operating temperature. Normally the DC resistance R_{20} at 20^0 C is given by the datasheet.

$$R_{20} = \frac{\rho_{20}}{S}$$
$$R' = R_0\left[(1 + \alpha_{20})\theta - 20)\right] \tag{3.4}$$

2. Calculate the skin and proximity factors of the conductor for use in the next step using the calculations presented in section 2.3.2.

3. Calculate the A.C. resistance using equation (2.5).

4. Calculate the dielectric losses W_d as per section 2.3.3.

5. Calculate the sheath loss factor for the screen by finding the sheath resistance and the reactance as per section 2.3.4 using double-bonding earth arrangement in trefoil for the single cable. As the conductor is not large segmental construction the eddy currents are negligible, giving the sheath loss as the total loss factor.

6. Calculate T_1 to give the insulation thermal resistance as per (3.5). The three-core cable can be treated individually and then summated.

$$T = \frac{\rho_{th}}{2\pi}\ln\left(1 + \frac{2t_1}{d_c}\right) \tag{3.5}$$

7. The next calculation is for the serving / jacket outside the screen. This is the same as the formula (3.5) except it deals with the different diameters.

8. The external thermal resistance of buried cables is then calculated using the equation below to give T_4 taking into account the thermal resistance of the soil.

$$T_4 = \frac{\rho_s}{\pi}\left[\ln(2u) + 2\ln(u)\right] \tag{3.6}$$

9. Then using the current calculation (3.3) the value of current that causes the conductor temperature to reach the maximum cable operating temperature is found.

There will be slight variations to this according to the type of cable used.

3.3.3. Variable and Emergency Load Conditions

The previous section dealt with steady state but it causes some concern when trying to establish the rate of temperature rise due to a step response. In this section, we will try to create a model that will assist in dealing with transient load variation to assist in answering the following questions;

1. Given the current operating conditions and a load increased by a given amount and sustained for a period what will be the temperature?

2. For a given time period, what is the maximum current the cable can carry so that the conductor temperature does not exceed a specified limit?

3. Based on the current operating conditions, how long can a new higher loading be applied without exceeding a specified temperature?

The first and second questions, if answered will be of assistance in the model validation due to the cyclic nature of the cable under test. The third part would assist in dealing with emergency ratings of cables and the duration the load can be sustained. This will also assist in acquiring the parameters for the protection relays as mentioned previously.

In assisting with the calculations in this section we will need to make some assumptions and one will be that the loading on the cables in question are identical and equal in load. In most three phase systems on the distribution network this may not be the case.

As per the previous section, the cable was expressed as a ladder network. This will still apply but it is reduced to a two-loop network.

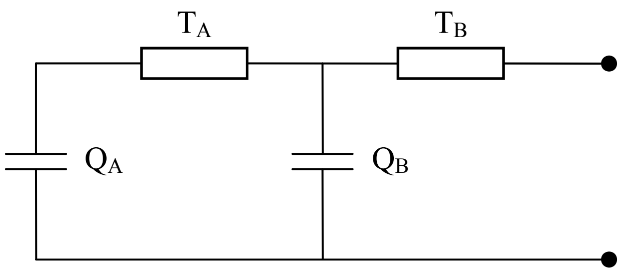


Figure 3.2 - Equivalent thermal network with two loops

Since this is a relatively simple circuit, it has been adopted by the IEC 60853 Part 1 and 2 as the standard and recommends that it be used for calculating transient responses. There are two types of responses, short and long term. The short term usually relates to durations longer than ten minutes to around an hour ($\leq \frac{1}{3} T \cdot Q$ for single core cables and $\leq \frac{1}{2} T \cdot Q$ for the total of three-core cables).

3.3.3.1. Short Term Transients

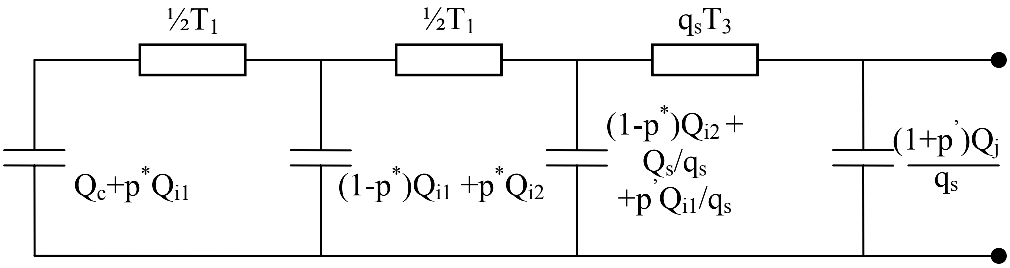


Figure 3.3 - Network for short duration

$$
\begin{aligned}
p^* &= \frac{1}{\ln\left(\frac{D_i}{d_c}\right)} - \frac{1}{\left(\frac{D_i}{d_c}\right) - 1} \\
p' &= \frac{1}{2\ln\left(\frac{D_e}{D_s}\right)} - \frac{1}{\left(\frac{D_e}{D_s}\right)^2 - 1}
\end{aligned}
\tag{3.7}
$$

$$
\begin{aligned}
&q_s = 1 + \lambda_1 \\
&Q_1 = Q_c + p^* Q_{i1} \qquad Q_2 = \left(1 - p^*\right) Q_{i1} + p^* Q_{i2} \\
&Q_3 = \left(1 - p^*\right) Q_{i2} \qquad Q_4 = \frac{Q_s + p' Q_{j1}}{q_s} \qquad Q_5 = \frac{Q_{j2}}{q_s}
\end{aligned}
\tag{3.8}
$$

$$
\begin{aligned}
&T_A = \frac{1}{2} T_1 \qquad Q_A = Q_1 \\
&T_B = \frac{1}{2} T_1 + q_s T_3 \\
&Q_B = Q_2 + \left[\frac{q_s T_3}{\frac{1}{2} T_1 + q_s T_3} \right]^2 \left(Q_3 + Q_4 \right)
\end{aligned}
\tag{3.9}
$$

Once these values are established, the cable partial transient needs to be attained by shorting out the right hand terminals in Figure 3.3. The transient resonse is as follows;

$$
M_0 = \frac{1}{2} \left(Q_A \left(T_A + T_B \right) + Q_B T_B \right) \tag{3.10}
$$

$$
N_0 = Q_A T_A Q_B T_B \tag{3.11}
$$

$$
a = \frac{M_0 + \sqrt{M_0^2 - N_0}}{N_0} \tag{3.12}
$$

$$
b = \frac{M_0 - \sqrt{M_0^2 - N_0}}{N_0} \tag{3.13}
$$

$$
T_a = \frac{1}{a - b} \left[\frac{1}{Q_A} - b \left(T_A + T_B \right) \right] \tag{3.14}
$$

$$
T_b = \left(T_A + T_B \right) - T_a \tag{3.15}
$$

The transient temperature rise of the conductor above the surface of the cable is

$$\theta_c(t) = W_c\left[T_a\left(1 - e^{-at}\right) + T_b\left(1 - e^{-bt}\right)\right] \tag{3.16}$$

The attainment factor for the transient rise between the conductor and outside surface of the cable;

$$a(t) = \frac{\theta_c(t)}{W_c(T_A + T_B)} \tag{3.17}$$

For direct buried cables the influence of the ground around the cable increases with time and may be significant within the short duration. The transient rise of the outer surface of the hottest cable within a group is;

$$\theta_e(t) = \frac{\rho_T W_1}{4\pi}\left(\left[-Ei\left(\frac{-D_e^2}{16t\delta}\right)\right] + \sum_{k=1}^{k=N-1}\left[-Ei\left(\frac{-(d_{pk})^2}{4t\delta}\right)\right]\right) \tag{3.18}$$

This finally leads us to the total transient temperature rise above ambient as;

$$\theta(t) = \theta_c(t) + a(t)\cdot\theta_e(t) \tag{3.19}$$

As temperature increases so does the electrical resistance and the resistance of any other metallic parts. To take this into consideration the following correction equation is used;

$$\theta_a(t) = \frac{\theta(t)}{1 + a(\theta(\infty) - \theta(t))} \tag{3.20}$$

3.3.3.2. Long Term Transients

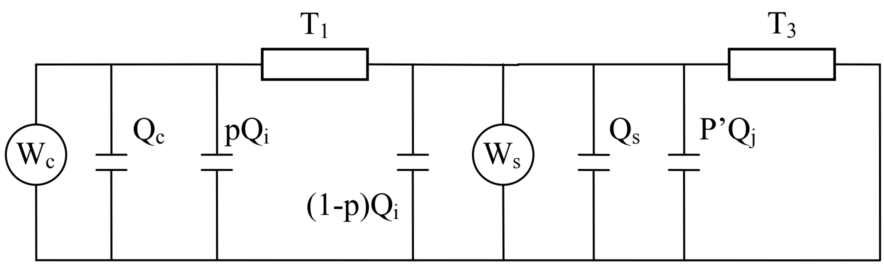


Figure 3.4 - Network for long duration

$$
\begin{aligned}
&T_A = T_1 \qquad\qquad Q_A = Q_c + pQ_i \\
&T_B = q_s T_3 \\
&Q_B = (1-p)Q_i + \frac{Q_s + p'Q_j}{q_s}
\end{aligned}
\tag{3.21}
$$

As per the short duration transients the formulae from (3.10) to (3.17) are identical except for (3.18) which is replaced by the one below.

$$
\theta_e(t) = \frac{\rho_T W_1}{4\pi}\left(\left[-Ei\left(\frac{-D_e^2}{16t\delta}\right)-\left[-Ei\left(\frac{-L^2}{t\delta}\right)\right]\right]+\sum_{k=1}^{k=N-1}\left[-Ei\left(\frac{-(d_{pk})^2}{4t\delta}\right)-\left[-Ei\left(\frac{(d_{pk})^2}{4t\delta}\right)\right]\right]\right) \tag{3.22}
$$

This long term transient would be vital in operation of the distribution network. In many cases, if a cable is to be subjected to extra load then it would be hours before alternative arrangements of the network is applied to alleviate the loading.

Chapter 4 - Results and Data Analysis

4.1. Data and Model Validation

As time restrictions for this research is crucial, the true validation of the model could not be fulfilled. Using Matlab the Steady State figure was for the following conditions; trefoil formation, soil resistivity is 1.2, the ground temperature at 25°C and the air at 40°C.

The model was run and the results below confirm with the manufacturers derating factors found in Table C.9 to Table C.11, with a slight error of couple of degrees.

Depth	0.8	1.0	1.3	1.5	1.8	2.0	2.5	3.0
Result	611.8	594.9	579.3	567.5	558.2	550.4	538.2	528.8

Soil Temp	10.0	15.0	20.0	25.0	30.0	35.0	40.0
Result	668.6	647.4	625.4	602.7	579.0	554.3	528.5

Soil Res	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Result	762.9	720.7	684.9	653.8	544.4	476.2	428.5	392.7	364.6	341.8

Table 4.1 - Steady State loading

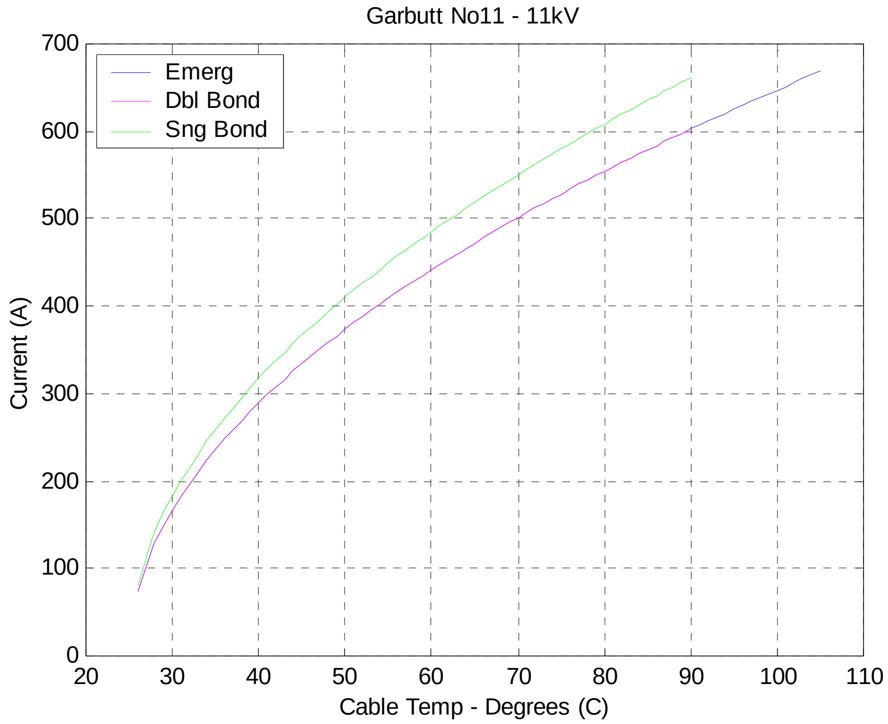


Table 4.2 - Effect of depth to ampacity

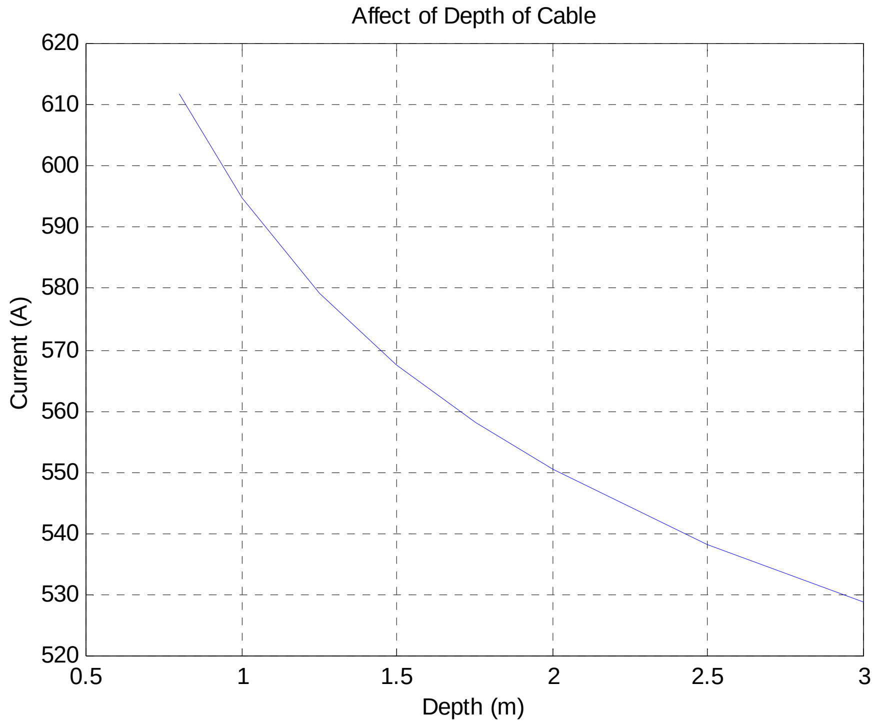


Table 4.3 - Soil temperature effect

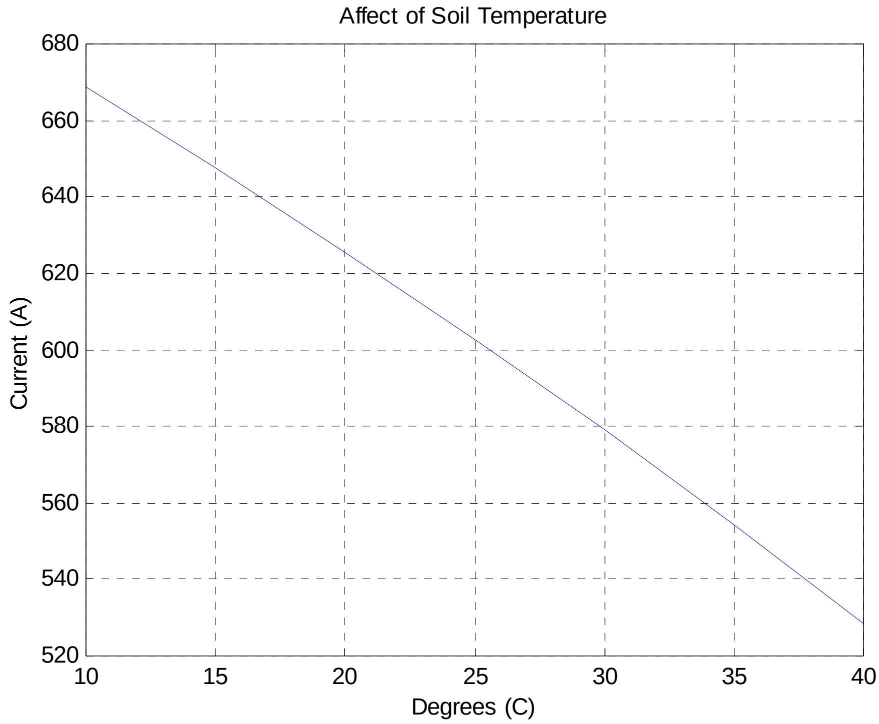


Table 4.4 - Soil resistance effects

4.2. Comparison with Commercial Packages

I had only been able to get one calculation done with the software SIROLEX, as the staff who normally use the software have been available either through work commitments or recreation leave. The configuration that was calculated did not match the actual layout of the cables. When I did run the model with the parameters that the software package was set to the results were reasonably close; the Sirolex value came out at 579 Amps and my model calculated 594 Amps.

4.3. Implementation

Due to the lack of time, the model was not completed to my satisfaction that it could be implemented into the real world. As I researched further into some of the issues I had in creating the model, it was found that certain properties of cable needed to be reviewed. These dealt with some of the heat transfer properties of cables due to the cable itself being round. Ideally it would have been appropriate to review some of these issues with finite element methodology.

Chapter 5 - Conclusion

In 1964, J.H. Neher presented a famous paper on the *Transient temperature rise of buried power cables* and opened his speech on this paper by remarking (cited in Anders 1997), 'The calculation of the transient temperature rise of buried cable systems, that is, the determination of the curve of conductor temperature rise versus time after the application of a constant current, has intrigued the more mathematically minded cable engineers for many years'.

5.1. Achievement of Project Objectives

The specific project objectives as required have been met as follows;

The researched information on the theory of heating of cables, the issues and the effects have on cables was far more intensive than originally thought. It was found that the Australian Standards dealt more with the minimum physical requirements of cables and the installation of these cables. These standards also dictate the recommended variable parameters such as soil and air temperatures to be used if they are not known. The IEC Standards are widely acceptable by the majority of publications as the recommended theoretical methods for calculating ampacity of cables using the earthing of sheaths, the thermal resistivity and capacitance found.

To assist in developing the model and comparing to real time temperature values of power cables under load, one substation that had ten 11kV power cables emanating from this substation was monitored. The data collected was used to compare the model created and the results from existing commercial software packages.

It was found that the Schweitzer SEL-3?? protection relays that are the current relays being used in Ergon's period contract do not have the capabilities for thermal protection or monitoring. Some of the relays in service from a previous period contract, the Micom P141, P142 and P143 models do have thermal protection capabilities. These relays with the understanding of the parameters required, which were uncovered in this project can be used to assist in protecting cables from possible degradation and failure.

From the research, a mathematical model was developed to predict the steady state value of current and the long term emergency load curve to suit the varying parameters such as the type of cable, the soil properties and other environmental factors such as air and ground temperatures. Further studies into the long term transient behaviour of cables is warranted to ensure that an accurate model could be implemented.

This model can be used in the SCADA system if the protection relays are not capable of thermal monitoring.

5.2. Project Outcomes

The aim of this project was to investigate the possible use of thermal protection for power cables and develop a model that can be implemented in real time. To achieve this objective a model for the power cable was developed using a thermal analogue model. This enabled dynamic ratings to be applied to the power cable with considerations of influencing factors such as cable type, installation, soil and air parameters and loading conditions. The model in its current state could be used with modifications of these parameters to suit its application in the electricity network.

Some assumptions had to be made since the experiment of monitoring temperatures of cables at the substation had a slight mishap where the sensor that was to be used to measure the soil temperature at the same depth of the laid cables was inadvertently misplaced back onto one of the cables. This error forced the use of an assumed ground temperature in the model.

Since Ergon Energy is standardising its sizes and types of cable to be used, then once these ratings are obtained, guidelines for the varying parameters can be tabulated and used in future calculations. In existing installations, individual calculations may be required for each cable if the standard in the area of interest in the electricity network has not been kept to a standard.

This approach can only be implemented if one of the following criteria can be met;

1. The cable current is monitored by SCADA

2. The relay protecting the cable has the capability for thermal protection such as the Micom P141/142/143.

The introduction of new technology and the ability to monitor real time cable temperatures is now a reality for the new installations of cables the methods I have created may be discarded. Since Ergon Energy has a vast number of existing cables in crucial positions of the electricity network and the possibility of remote monitoring is still small, the modelling can prove its worth.

One aspect that became evident during this project was that in many areas of the existing network, the model actually de-rated the current capacity of the cables. This led to speculation by the Network Operations Control Centre staff who question the standards and the models by stating that they have been operating the cables well beyond the new ratings for many years with no mishap. This argument was recently unfounded when a cable was dug up and exposed to find that overheating had occurred and the conduit that housed the cable actually deformed dramatically. It is not known as to how much damage the insulation had sustained.

To assist in gaining acceptance and further verification of this idea it is envisaged that only the thermal protection be set only to initiate alarms and not to actually trip any feeder circuits. This will remove any possible inconvenience that may be caused by possible incorrect parameters being employed into the algorithms.

5.3. Further Work

In the current state of this project further analysis into transients and load curve fitting is appropriate. This could then be reviewed as to whether it will fit into the parameters of the protection relay requirements as they stand today. Another element for future work is to convert the model using finite element methods. This should give the user a reasonable idea of heating in the surrounds especially where there are groups of circuits in close proximity.

The introduction of fibre optics into temperature monitoring appears to have taken a dramatic upward trend. While I was preparing this project over 6 months ago my work group was able to convince Ergon management to include in its standard cable specifications for purchasing that the cable have integrated in its insulation the fibre optic cable especially for areas that are regarded as possibly critical in the future. For a small additional cost per metre of cable (approximately two dollars), the ability to use Distributed Temperature Sensing will become a reality and far more accurate models can be developed for those cables that are do not have the fibre optics embedded within.

References

ALSTOM T&D 2004, *Micom P141, P142, P143 Feeder Management Relays Technical Guide for Software 0200G,* St Leonards Avenue, Stafford, ST17 4LX England.

Anders, George J., 1997, *Ratings of Electrical Power Cables - Ampacity Computations for Transmission, Distribution and Industrial Applications,* Institute of Electrical and Electronics Engineers Press, New York.

Anders, George J., 2004, *Rating of Electric Power Cables in Unfavorable Thermal Environment.*, Institute of Electrical and Electronics Engineers Press, New York.

ANSI/IEEE Standard 575, 1988, *Application of Sheath-Bonding Methods for Single Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths,* Institute of Electrical and Electronics Engineers, New York.

Australian/New Zealand Standard 2006, *AS/NZS 1429.1:2006 Electric cables - Polymeric insulated Part 1: For working voltages 1.9/3.3 (3.6) kV up to and including 19/33 (36) kV,* Standards Australia, Sydney, and Standards New Zealand, Wellington.

Australian/New Zealand Standard 2006, *AS/NZS 1429.2:1998 Electric cables - Polymeric insulated Part 2: For working voltages above 19/33 (36) kV up to and including 76/132 (145) kV*, Standards Australia, Sydney, and Standards New Zealand, Wellington.

Brown George 2003 , (Date Accessed 08 October 2006)
http://www.ptac.org/eet/dl/eett0401p.pdf

CMA Power Cables, 1987, *Solid Type Paper Insulated Lead and Aluminum Sheathed Conductors for Voltages up to 19/33 kV*, Cable Makers Australia.

Cooper, J, 2003, *Ampacity and Sheath Bonding,* ICC 2003 Fall Educational Session.

Ergon Energy Corporation Limited 2000, *Network Planning Criteria – Deliverable NP02,Version 2.03*, Network Asset Management, Ergon Energy Corporation, Queensland.

ICNIRP (1998), '*Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields*', Health Physics 74(4), 494–515.

IEC Standard, 2001, *IEC Standards 60287-1-1 Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General*, IEC Press, Geneva.

IEC Standard, 2002, *IEC Standards 60287-1-3 Electric cables - Calculation of the current rating - Part 1-3: Current rating equations (100 % load factor) and calculation of losses - Current sharing between parallel single-core cables and calculation of circulating current losses*, IEC Press, Geneva.

IEC Standard, 2001, *IEC Standards 60287-2-1 Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of thermal resistance*, IEC Press, Geneva.

IEEE Standard, 1994, *IEEE Standard 835 - Power Cable Ampacity Tables,* IEEE Press, New York.

Kraus, JD and Fleisch, D 1999, *Electromagnetics with Applications*, McGraw-Hill, Singapore.

Landinger, C, n.d., *Basic Cable Characteristics Part II*, Hendrix Wire and Cable, viewed 20 May 2006, <http://www.ewh.ieee.org/soc/pes/icc/subcommittees/subcom_e/education/2001/f2001_landinger.pdf>

Langsley, J, 2004, *Distributed Temperature Monitoring of Cables*, TechCon 2004, Sydney.

Neher, J and McGrath, M (1957), *Calculation of the Temperature Rise and Load Capability of Cable Systems*, AIEE Trans., Vol. 76, Part 3, pp. 755-772.

Queensland Department of Energy 2006, (Date Accessed 09 October 2006), URL: http://www.energy.qld.gov.au/electricity_in_queensland.cfm

Wijeratna, D, Lucas, J, Peiris, H and Perera, H 2003, 'Development of a Software Package for Calculating Current Rating of Medium Voltage Power Cable', *Transactions of the IEE Sri Lank*, September 2003, pp.50-57

Zocholl, S and Guzman, A, 1999, Thermal Models In Power System Protection, SEL, USA.

Appendix A - Project Specification

USQ

AUSTRALIA

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/2 Research Project
PROJECT SPECIFICATION

FOR:	**Cosmas Gianoulis**
TOPIC:	Investigate the use of thermal protection for underground cables in ERGON Energy's electricity network
SUPERVISOR:	Dr Tony AhFock
PROJECT AIM:	The proposed research project is to investigate and evaluate the use of thermal protection for underground cables.

PROGRAMME: **Issue A, 28 March 2006**

1. Research background information on the theory of heating of cables, the issues and the effects. Research information on the current Australian and Ergon Energy's Standards to the thermal rating of cables that are being used and the effect of the varying methods of enclosures for cables.
2. Collate the feeder cable temperatures that are being monitored at an Ergon Substation and the type of enclosures i.e. the soil backfill, type of cable and its properties also the ambient and ground temperatures.
3. Compare the data collected in (2) and compare the results with existing software packages in use in Ergon.
4. Research and understand the capabilities of the Schweitzer SEL-3?? Protection Relays for possible thermal protection implementation.
5. Develop a mathematical model to predict the temperature curve to suit the varying parameters such as the type of cable, the soil properties, the load curve for the cable and other environmental factors such as air and ground temperatures to use in the relay in (5).

As time permits

6. If in (5) it is not possible for the relay to employ the thermal protection, then review the possibility of the SCADA RTUs to facilitate the function.
7. Programme the SEL-3?? Relays for thermal protection and test.
8. Evaluate the possibility of extending the use of the model in (5) above to other protection relays in Ergon's network.

For a C grade steps 1 to 4 must be completed and a good attempt at step 5 is expected. In addition the dissertation must be of acceptable standard.

For an A grade or higher steps 1 to 5 must be successfully completed and the dissertation must be of significantly better than average standard.

AGREED: ____________ (student) A. Ahfock (supervisor)

(dated) 31 / 3 / 06

Appendix B - Standard Cable Data

Table B.1 - Maximum continuous conductor temperatures for PLYS up to 36kV (AS 1026-2004 Table 1)

Voltage rating of cable kV	Type of cable	Maximum temperature °C
0.6/1 (1.2) 3.8/6.6 (7.2)	All types	80
6.35/11 (12) 11/11 (12)	Single-core Three-core screened Three-core belted	70 70 65
12.7/22 (24) 19/33 (36)	All types	65
NOTE: The temperatures given in this table are only for cables laid either direct in the earth or in thermal conditions equivalent to direct burial. Reference should be made to ERA 69.30, Part 1 for temperatures relating to other conditions of operation.		

Table B.2 - Maximum conductor temperature for the specified insulation material and for different modes of operation (AS 1429.1-2006 Table 1.2)

Insulation material	Maximum conductor temperature, °C (Note 1)		
	Continuous operation	Emergency operation (Note2)	Short-circuit operation (5s maximum duration)
XLPE	90	105	250
EPR	90	130	250

NOTES:

1. The maximum conductor temperatures specified are based upon the properties of the insulation materials but in practice may need to be derated to take account of —
   (a) joints and terminations; and
   (b) installation conditions, such as proximity to other circuits and services.

2. The emergency operation temperatures are applicable for an average over several years, of not more than one period per year. No period should exceed 36 h and there should not be more than three periods in any 12 consecutive months.

Table B.3 - Skin and proximity effects

Experimental values for the coefficients k_s and k_p (IEC 60287-1-1 Table 2)

Type of conductor	Whether dried and impregnated or not	k_s	k_p
Copper			
Round, stranded	Yes	1	0,8
Round, stranded	No	1	1
Round, segmental [a]	Yes	0,435	0,37
Hollow, helical stranded	Yes	[b]	0,8
Sector-shaped	No	1	0,8
Sector-shaped	Yes	1	1
Aluminium	Either		[d]
Round, stranded	Either	1	
Round, 4 segment	Either	0,28	
Round, 5 segment	Either	0,19	
Round, 6 segment	Either	0,12	
Segmental with peripheral strands	Either	[c]	

a The values given apply to conductors having four segments (with or without central duct) and sectional areas less than 1 600 mm2. These values apply to conductors in which all the layers of wire have the same direction of lay. The values are provisional and the subject is under consideration.

b The following formula should be used for k_s:

$$k_s = \left(\frac{d_c^{'} - d_i}{d_c^{'} + d_i}\right)\left(\frac{d_c^{'} + 2d_i}{d_c^{'} + d_i}\right)^2$$

where

d_i is the inside diameter of the conductor (central duct) (mm);

d_c is the outside diameter of the equivalent solid conductor having the same central duct (mm).

c The following formula should be used to calculate k_s for cables having a conductor which consists of a central segmental portion surrounded by one or more layers of strands.

$$k_s = \left\{12c\left[(\alpha c - 0.5)^2 + (\alpha c - 0.5)(\psi - \alpha)c + 0.33(\psi - \alpha)^2 c^2\right] + b\left(3 - 6b + 4b^2\right)\right\}^{0.5}$$

where

b is the ratio of the total cross-sectional area of the peripheral strands to the total cross-sectional area of the complete conductor.

c is the ratio of the total cross-sectional area of the segmental conductor to the total cross-sectional area of the complete conductor, $c = (1-b)$.

$$\alpha = \frac{1}{(1 + \sin \pi / n)^2}$$

$$\psi = \frac{2\pi / n + 2/3}{2(1 + \pi / n)}$$

where

n is the number of segments.

This formula is applicable to aluminium conductors up to 1 600 mm^2.

If the total cross-sectional area of the peripheral strands exceeds 30 % of the total cross-sectional area of the conductor, then k_s may be regarded as unity.

d Although there are no accepted experimental results dealing specifically with the coefficient k_P for aluminium conductors, it is recommended that, for stranded aluminium conductors, the values given for similar copper conductors are used.

Table B.4 - ε and tan δ values for insulation of power cables

Type of cable	ε	tan δ
Cables insulated with impregnated paper		
Solid type, fully-impregnated, pre-impregnated or mass-impregnated non-draining	4	0.01
Oil-filled, self-contained up to Uo = 36 kV	3.6	0.0035
up to Uo = 87 kV	3.6	0.0033
up to Uo = 160 kV	3.5	0.0030
up to Uo = 220 kV	3.5	0.0028
Oil-pressure, pipe-type	3.7	0.0045
External gas-pressure	3.6	0.0040
Internal gas-pressure	3.4	0.0045
*Cable with other kinds of insulation*5)		
Butyl rubber	4	0.050
EPR		
up to and including 18/30 (36) kV cables	3	0.020
greater than 18/30 (36) kV cables	3	0.005
PVC	8	0.1
PE (HD and LD)	2.3	0.001
XLPE		
up to and including 18/30 (36) kV cables (unfilled)	2.5	0.004
greater than 18/30 (36) kV cables (unfilled)	2.5	0.001
greater than 18/30 (36) kV cables (filled)	3.0	0.005
PPL		
equal to, or greater than 63/110 kV cables	2.8	0.0014

Table B.5 - Phase to ground voltage where dielectric loss should be calculated

Type of cable	Uo (kV)
Cables insulated with impregnated paper	
Solid-type	38.0
Oil-filled and gas-pressure	63.5
Cables with other types of insulation	
Butyl rubber	18.0
EPR	63.5
PVC	6.0
PE (HD and LD)	127.0
XLPE (unfilled)	127.0
XLPE (filled)	63.5

Table B.6 - Australian standard conditions to use

1) *Standard conditions*

Soil thermal resistivity	1,2 K.m/W
Soil ambient temperature	25 °C summer
	18 °C winter

2) *Depth of laying*

Measured from the ground surface to the centre of the cable, or to the centre of a trefoil group.

L.V. cables	500 mm under footways
	750 mm under roadways
11 kV cables	800 mm under footways
	800 mm under roadways
33 kV cables and higher voltages	1 000 mm under footways
	1 000 mm under roadways

3) *Air ambient temperature*

Maximum value	40 °C summer
	30 °C winter

Table B.7 - Ergon Energy's Standard Cable List

List of Ergon Energy Standard Cables - Amended June 2005

Olex Product Code	Ergon Energy Item Number	Protection	Volts	Size	Material	Cores	Insulation etc	Fault	Extras
XLYA32AA001	85	Not Insect Protected	22kV	630mm	Al	1Core		13.7kA	DTS
XLYA25TD003	86		22kV	185mm	Al	Triplex		10kA	
XJNA25TD003	90		11kV	185mm	Al	Triplex			
XJNA18TD003	93		11kV	35mm	Al	3Core			
XDDG37AA004	83		LV	240mm	Al	4Core			
HEVP15RP004	82		LV	16mm	Cu	4Core			
			LV	4mm	Cu	2Core			
XLNA18TB003	87	Insect Protected	22kV	35mm	Al	Triplex	XLPE/PVC/ DBT/HDPE	3kA	
XJZP28VY001	Non Contract Item		11kV	**400mm**	Cu	1Core		13kA	DTS
XJNP26TB003	91		11kV	240mm	Cu	Triplex		13.1kA	DTS
XJNA25TB003	89		11kV	185mm	Al	Triplex		10kA	
XJNA18TB003	92		11kV	35mm	Al	Triplex		3kA	
XDDG37ME004	84		LV	240mm	Al	4Core	XLPE/PVC/ NYL/HDPE		
			LV	**50mm**	Cu	4Core			
LDZP15RP004	81		LV	16mm	Cu	4Core			
			LV	4mm	Cu	2Core			

Appendix C - GA11 Feeder Data

The cables selected for the test were 3 single core XLPE/HDPE 400mm^2 copper cables. In this appendix will be the relevant manufacturer's data and as installed data that was used in testing the model.

Table C.8 - Manufacturer's cable data and installation details

Manufacturer Data			
Conductor Type	Copper – round, stranded	Conductor DC Resistance @ 20°C	0.0470 Ω / km
Conductor Area / diameter	400 mm^2 / 23.6 mm	Conductor AC Resistance @ 50Hz and 90°C – Trefoil or flat touching	0.0631 Ω / km
Average insulation thickness	3.4 mm	Inductive reactance @ 50Hz and 90°C - Trefoil	0.100 Ω / km
Nominal Diameter over insulation	32.1 mm	Conductor to screen capacitance	0.569 µF / km
Wire screen area	68.7 mm^2	Charging current per phase	1.13 A / km
Diameter over wire screen	33.6 mm	Dielectric Loss per phase	28.8 W / km
Overall diameter	41.5	Screen DC Resistance @ 20°C	0.270 Ω / km
Current Rating for trefoil with air temperature @ 40°C and the ground temperature at 25°	605 A		
Installation details			
Laid formation	Trefoil	Depth	900 mm
Ground Temperature	25°C	Ambient Temperature	40°C
Soil Resistivity	1.2 °C m/W		

Table C.9 - Rating factors for soil temperature variation

For cable laid direct							
Ground Temperature	10	15	20	25	30	35	40
Rating Factor	1.11	1.07	1.04	1.00	0.96	0.92	0.88

Table C.10 - Rating factors for cable depth

Depth of burial (m)	Rating factor up to 300m2	Rating factor above 300m2	Rating factor (single core)	Rating factor (three core)
0.80	1.00	1.00	1.00	1.00
1.00	0.98	0.97	0.98	0.99
1.25	0.96	0.95	0.95	0.97
1.50	0.95	0.93	0.94	0.96
1.75	0.94	0.91	0.92	0.96
2.00	0.92	0.89	0.91	0.95
2.50	0.91	0.88	0.89	0.94
3.00	0.90	0.86	0.88	0.93

Table C.11 - Soil resistivity derating factors

Soil Res °C m/W	0.7	0.8	0.9	1	1.5	2	2.5	3	3.5	4
Factor	1.23	1.17	1.12	1.07	0.91	0.8	0.73	0.67	0.62	0.58

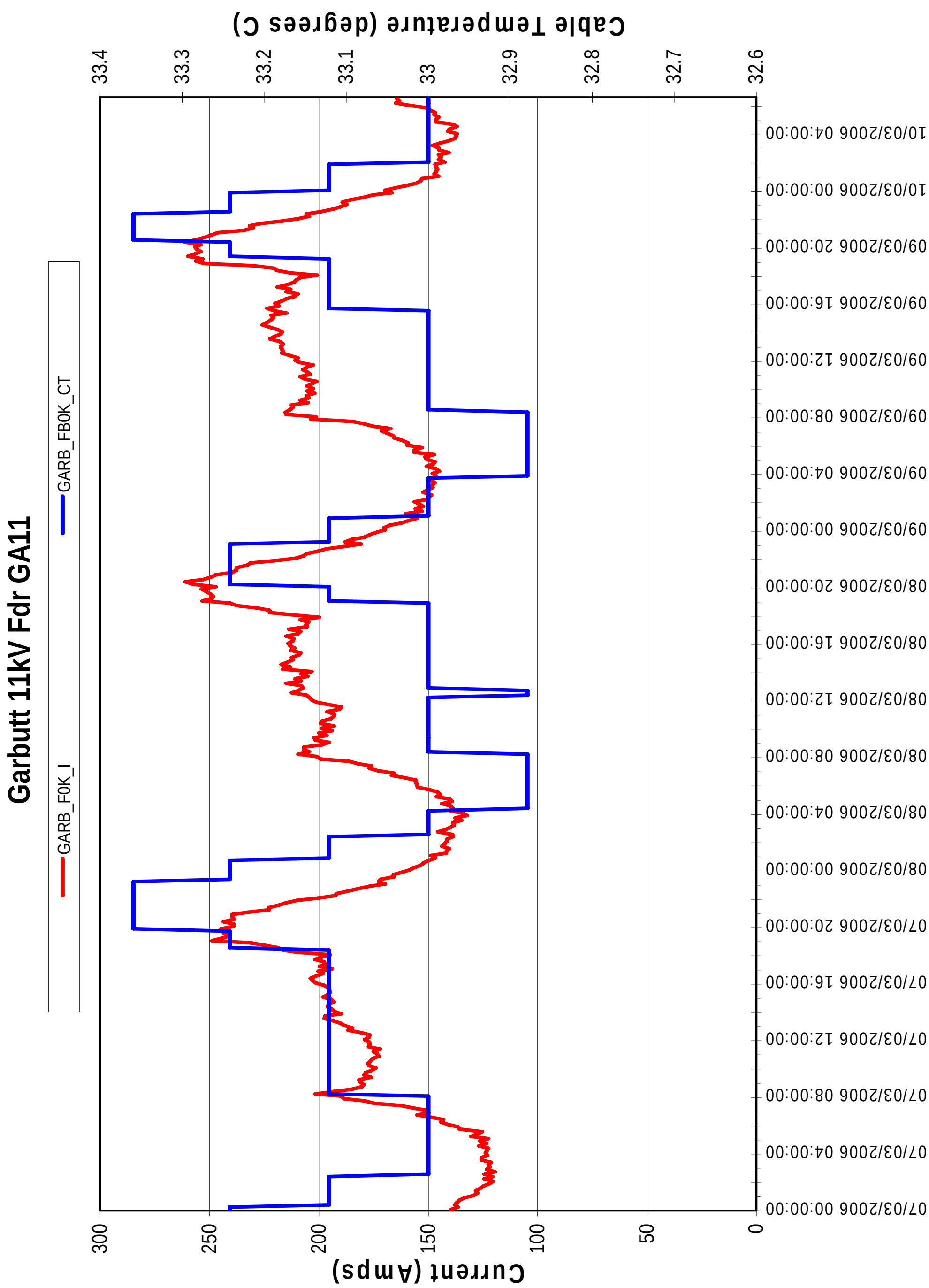


Figure C.1 - Temperature against Load - Real Data

Table C.12 - Output from Sirolex program

Olex 400 mm² Cu 6.35/11 kV XLPE CWS/PVC/NYL/HDPE

V030829

Conductor	No. of cables	3	
	Material	Plain Annealed Copper	
	Form	Compacted circular	
	Area	400	mm²
	No. of wires	58	
	Wire diameter	N/A	mm
	Rdc at 20°C	0.047	Ohm/km
	Diameter	23.6	mm
Conductor screen	Diameter	24.8	mm
Insulation	Material	XLPE (HV)	
	Vpe	6.35	kV
	Vpp	11	kV
	Diameter	31.80	mm
Insulation screen	Diameter	33.60	mm

Core screen 1	Type	Copper wire/braid		
	No. of wires	Diameter	Lay length	
	40	1.7	279	
	Diameter	37.00	mm	
Core screen 2	Type	None		
	Diameter		mm	
Armour beddinc	Material	PVC		
	Diameter	40.10	mm	
Armour	Type	None		
	Diameter		mm	
Sheath	Material	Nylon		
	Diameter	41.90	mm	
Covering	Material	HDPE		
	Diameter	46.20	mm	

PERFORMANCE DATA

		Cables, trefoil touching	Cables, flat touching	Cables, flat spaced	Ducts, trefoil touching	Ducts, flat touching	Ducts, flat spaced	
Conductor ac resistance at 90°C		0.0627		0.0616	0.0618		0.0614	Ohm/km
Inductive reactance		0.1023	0.1226	0.1683	0.1330	0.1549	0.2005	Ohm/km
Cable pf		0.5228	0.4554	0.3439	0.4215	0.3707	0.2928	
3p volt drop	- maximum	0.2078	0.2386	0.3104	0.2540	0.2888	0.3633	mV/A.m
	- at load pf	0.1932	0.2143	0.2603	0.2239	0.2466	0.2935	mV/A.m

Core screen 1	- dc resistance at 20°C	0.2043	Ohm/km
	- dc resistance at 90°C	0.2606	Ohm/km
Core screen 2	- dc resistance at 20°C	0.0000	Ohm/km
	- dc resistance at 90°C	0.0000	Ohm/km
Armour	- dc resistance at 20°C	0.0000	Ohm/km
	- dc resistance at 90°C	0.0000	Ohm/km

Conductor to screen capacitance	0.514	µF/km
Charging current	1.03	A/km/phase
Dielectric loss	26	W/km/phase
Zero sequence resistance at 20°C	0.2530	Ohm/km
Zero sequence resistance at 90°C	0.3218	Ohm/km
Zero sequence reactance	0.0419	Ohm/km

MATERIAL PROPERTIES

Insulation	- thermal resistivity	3.5	K.m/W
	- relative permittivity	2.3	
	- loss factor	0.004	
	- solar absorption coefficient	0.4	
Armour bedding thermal resistivity		5.0	K.m/W
Sheath	- thermal resistivity	5.0	K.m/W
	- solar absorption coefficient	0.6	
Covering	- thermal resistivity	3.5	K.m/W
	- solar absorption coefficient	0.4	
Duct in air	- thermal resistivity	6.0	K.m/W
	- solar absorption coefficient	0.6	
Duct in ground thermal resistivity		6.0	K.m/W

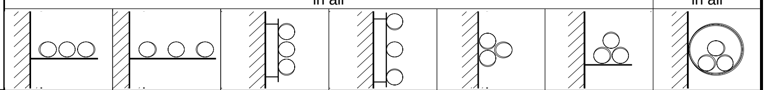
OPERATING CONDITIONS

Supply frequency	50	Hz
Load power factor	0.8	
Conductor operating temperature	90	°C
Ambient air temperature	40	°C
Solar radiation intensity	0	W/m²
Ambient ground temperature	27	°C
Depth of burial, to cable/group axis	900	mm
Thermal resistivity of ground	1.2	K.m/W
Non standard axial spacing between cables		mm
Non standard axial spacing between ducts		mm

Ducts	Type in air		PVC	
	Type in ground		PVC	
		Nominal size	Actual OD, mm	Actual ID, mm
In air	Single cable	65 mm	75.35	66.2
	Three cables	150 mm	160.25	141.4
In ground	Single cable	65 mm	75.35	66.2
	Three cables	150 mm	160.25	141.4

CURRENT RATINGS

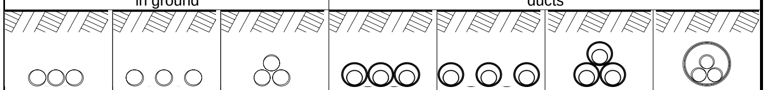
Thermal resistances				
- Insulation	0.1968	K.m/W		
- Bedding	0.0640	K.m/W		
- Sheath	0.0349	K.m/W		
- Covering	0.0544	K.m/W		



		Unenclosed in air						Enclosed in air
Continuous current rating	A	677	707	685	668	679	724	489
External thermal resistance	K.m/W	0.8594	0.5565	0.8333	0.6531	1.0989	0.9286	2.4023
Cable surface temperature	°C	76	71	75	73	78	76	84
Screen loss factor		0.5229	1.0080	0.5229	1.0080	0.2234	0.2234	0.2234
Armour loss factor		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Screen bonding

Bonded at both ends



		Direct in ground			Underground ducts			
Continuous current rating	A	529	479	572	445	405	483	495
External thermal resistance	K.m/W	2.0676	1.9666	2.1347	2.5099	2.4100	2.6693	3.0315
Cable surface temperature	°C	81	80	80	82	82	83	83
Screen loss factor		0.5229	1.0080	0.2234	0.8595	1.3651	0.4750	0.2234
Armour loss factor		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

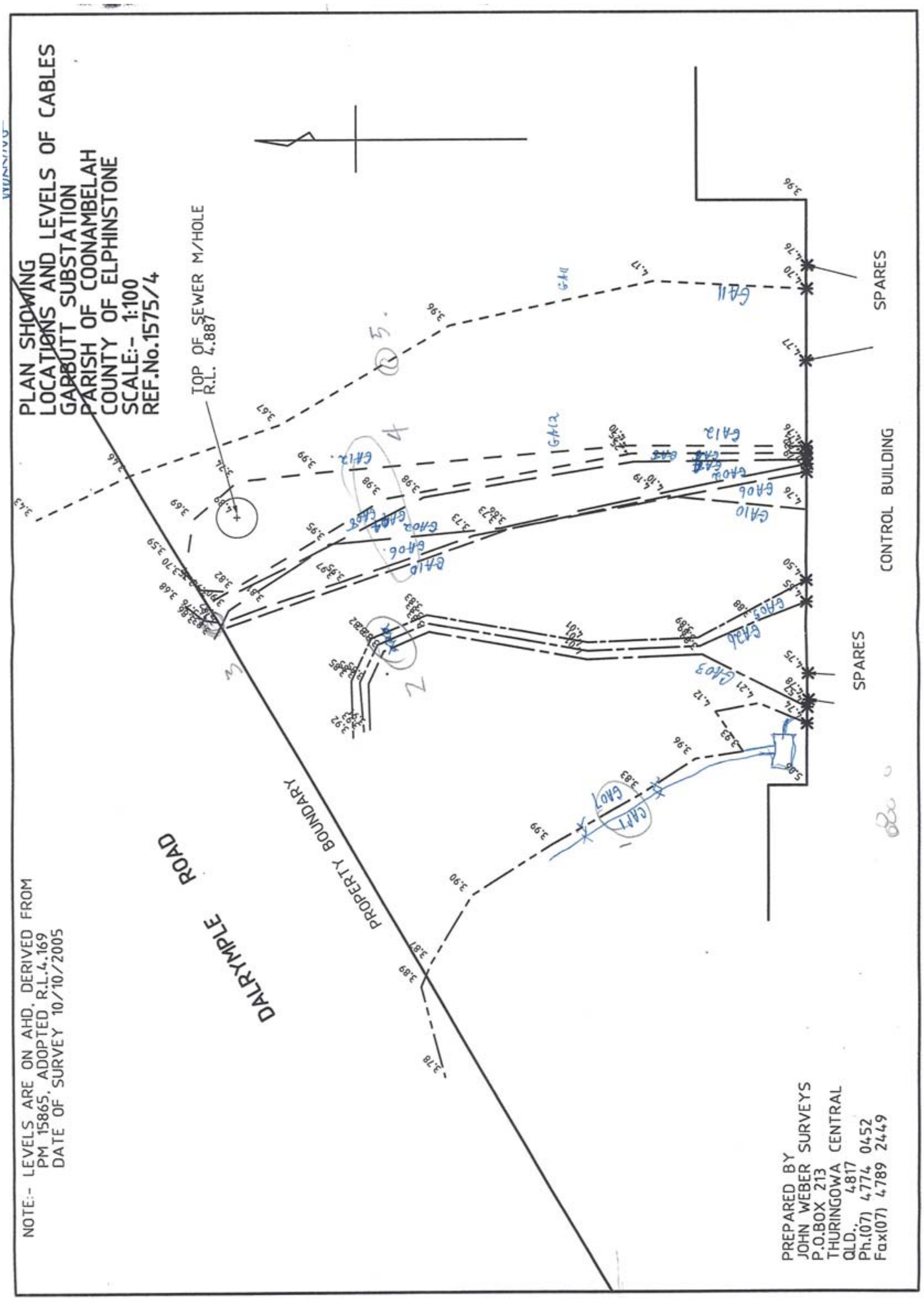


Figure C.2 - Location of RTDs

Appendix D - Protection Relay Information

Figure D.3 - SEL Feeder Management Relay

Figure D.4 - Micom P14x Feeder Management Relay

Appendix E - Matlab Files

```
%TestSteadyState
%Program to find the steady current values
%that will keep the temperature at or below
%the maximum operating temperature.

close all;
clear all;

f=50;
w=2*pi*f;
rho20=0.0470*10^-3;         %Cable data

a20=0.00393;
S=400;                      %Conductor Area
Ss=68.7                     %Screen Area
s=46.2;                     %Trefoil formation
%s=2*46.2;                  %Flat spaced

dc=23.6;                    %conductor O/D
theta_max=90;               %max temperature
theta_s = 25;               %soil temperature
theta_emerg = 105;          %emergency temperature
n=1;                        %number of conductors in cable
RhoT4 = 1.2;                %soil resistivity
ks=1;
kp=0.8;
e_perm=2.3;
tandelta=.004;
Di=33.6;                    %Insulation O/D
U=11000;
XLPE_OD=31.8;               %XLPE Insulation O/D
SCR_OD=37;                  %Screen O/D
J_OD=41.9;                  %Jacket O/D
SERV_OD=46.2;               %Serving O/D
sheath_rho20=0.00027;       %Cable data
sheath_a20=a20;
L = 900;                    %Depth of cable
c_COPPER = 3.45;            %specific heat for Copper
c_XLPE = 2.4;           %specific heat for XLPE
c_PVC = 1.76


%AC Resistance Calcs
Rdc=rho20*(1+a20*(theta_max-20))

Fk=(4*w*10^-7)/Rdc;
xs=(Fk*ks);
ys=xs^2/(192+0.8*xs^2)
xp=(Fk*kp);
Fp=xp^2/(192+0.8*xp^2);
yp=Fp*((dc/s)^2)*(0.312*((dc/s)^2)+1.18/(Fp+.27))

R=Rdc*(1+ys+yp)

%dielectric losses
C=e_perm/(18*log(Di/dc))*10^-9
Uo=U/sqrt(3);
Wd=w*C*Uo^2*tandelta
```

```
%sheath loss factor
ts=3.4;

%sheath resistance
Rs_dc=sheath_rho20*[1+a20*(theta_s-20)]

%sheath reactance
Xm=f*8.71*10^-7
X=2*w*10^-7*log(2*s/Di);

lambda_1=(Rs_dc/R)*1/(1+(Rs_dc/X)^2);
lambda__1=0;

%total sheath loss factor
lambda1=lambda_1 + lambda__1

%total armour loss factor
lambda2 = 0

%thermal resistance
rhoT1=3.5;
t1=(Di-dc)/2;
T1=rhoT1/(2*pi)*log(1+2*t1/dc)

%jacket thermal resistance
tj = J_OD - SCR_OD;
Ds = SCR_OD;
rhoT2 = 5;

%T2=rhoT2/(2*pi)*log(1+2*tj/Ds)
T2=0

%outer serving resistance
rhoT3 = 3.5;
to = (J_OD-SCR_OD)/2;
Do = SCR_OD;

T3=rhoT3/(2*pi)*log(1+2*to/Do)

%outer to soil  resistance
De = SERV_OD;

%For Trefoil Formation
Trefoil_C= L-sqrt(s^2+(s/2)^2)/2;
u=(2*Trefoil_C)/De;
T4=1.5*RhoT4/pi*[log(2*u)-0.630]

%For flat formation spaced
%u=2*L/De;
%T4=RhoT4*log((2*u)*(1+(2*L/s)^2))/(2*pi)


%steady state - Double Bond
r=0;
for dTheta=1:theta_max-theta_s
    r=r+1;
    Idb(r) = steadystate_trans(dTheta, R, Wd, n, lambda1, lambda2,
[T1, T2, T3, T4]);
end
Idb(r)
```

```
%steady state - Single Bond
r=0;
for dTheta=1:theta_max-theta_s
    r=r+1;
    Isb(r) = steadystate_trans(dTheta, R, Wd, n, 0, lambda2, [T1, T2,
T3, T4]);
end
Isb(r)

%steady state - Double Bond - Emergency
r=0;
for dTheta=1:theta_emerg-theta_s
    r=r+1;
    Iem(r) = steadystate_trans(dTheta, R, Wd, n, lambda1, lambda2,
[T1, T2, T3, T4]);
end
Iem(r)

k1=theta_s+1:theta_max;
k2=theta_s+1:theta_emerg;
plot(k2,Iem,'b', k1, Idb, 'm', k1, Isb, 'g'), title('Steady State'),
xlabel('Cable Temp - Degrees (C)'), ylabel('Current (A)');
grid on;

legend ('Emerg','Dbl Bond', 'Sng Bond', 2);

%For tests
Depth = [.8, 1, 1.25, 1.5, 1.75, 2, 2.5, 3];

for r=1:length(Depth);
    L1=Depth(r)*1000;
    dTheta = theta_max-theta_s;
    %For Trefoil Formation
    Trefoil_C= L1-sqrt(s^2+(s/2)^2)/2;
    u=(2*Trefoil_C)/De;
    T4=1.5*RhoT4/pi*[log(2*u)-0.630]
    Id(r) = steadystate_trans(dTheta, R, Wd, n, lambda1, lambda2,
[T1, T2, T3, T4]);
end

dlmwrite('DepthTest.txt',Id, '\t');
figure;
plot(Depth,Id),title('Affect of Depth of Cable'), xlabel('Depth
(m)'), ylabel('Current (A)');

grid on;
clear Id;
SoilTemp = 10:5:40;
for r=1:length(SoilTemp);
    dTheta = theta_max-SoilTemp(r);
    %For Trefoil Formation
    Trefoil_C= L-sqrt(s^2+(s/2)^2)/2;
    u=(2*Trefoil_C)/De;
    T4=1.5*RhoT4/pi*[log(2*u)-0.630]
    Id(r) = steadystate_trans(dTheta, R, Wd, n, lambda1, lambda2,
[T1, T2, T3, T4]);
end

figure;
```

```
plot(SoilTemp,Id),title('Affect of Soil Temperature'),
xlabel('Degrees (C)'), ylabel('Current (A)');

grid on;

dlmwrite('SoilTempTest.txt',Id, '\t');

SoilRes = [0.7, 0.8, 0.9, 1.0,1.5, 2.0, 2.5, 3.0, 3.5, 4.0]
clear Id;
for r=1:length(SoilRes);
    dTheta = theta_max-theta_s;
    %For Trefoil Formation
    Trefoil_C= L-sqrt(s^2+(s/2)^2)/2;
    u=(2*Trefoil_C)/De;
    T4=1.5*SoilRes(r)/pi*[log(2*u)-0.630]
    Id(r) = steadystate_trans(dTheta, R, Wd, n, lambda1, lambda2,
[T1, T2, T3, T4]);
end

figure;
plot(SoilRes,Id), title('Affect of Soil Resistance'), xlabel('Soil
Resitivity (oC w/m)'), ylabel('Current (A)');


grid on;

dlmwrite('SoilResTest.txt',Id, '\t');




function I = steadystate_trans(dTheta, R, Wd, n, lambda1, lambda2, T)
%
%
%  Function to calculate the steady state of a cable
%
%
%  Usage:
%           I  = steadystate_trans(dTheta, R, Wd, n, lambda1,
lambda2, T);
% Inputs:
%           dTheta = O/Diameter of the conductor
%           R = O/Diameter of the insulation
%           Wd = O/Diameter of the screen
%           n = O/Diameter of the jacket
%           lambda1 = loss factor - sheath
%           lambda2 = loss factor - armour
%           T  = array that hold T1, T2, T3, T4

% Outputs:
%           I  = Steady state current
%
%

I_1 = dTheta - Wd*[0.5*T(1)+n*(T(2)+T(3)+T(4))];
I_2 =
R*T(1)+n*R*(1+lambda1)*T(2)+n*R*(1+lambda1+lambda2)*(T(3)+T(4));
I = (I_1/I_2)^0.5;

%Eof
```

```
function [TA, TB, QA, QB] = short_trans(Dc, Di, Ds, Dj, L1, S, Ss, T)
%
%
%  Function to calculate the Short Transient response of a cable
%
%
%  Usage:
%         [TA, TB, QA, QB] = short_trans(Dc, Di, Ds, Dj, L1, S, Ss);
% Inputs:
%          Dc = O/Diameter of the conductor
%          Di = O/Diameter of the insulation
%          Ds = O/Diameter of the screen
%          Dj = O/Diameter of the jacket
%          L1 = sheath loss factor
%          S  = Cros sectional area of conductor
%          Ss = Cros sectional area of screen
%          T  = array that hold T1, T2, T3

% Outputs:
%          TA = Thermal Resistance for 1st part
%          TB = Thermal Resistance for 2nd part
%          QA = Thermal Capacitance for 1st part
%          QB = Thermal Capacitance for 2nd part
%
%
%Short term transient response
c_COPPER = 3.45;        %specific heat for Copper
c_XLPE = 2.4;           %specific heat for XLPE
c_PVC = 1.76            %specific heat for PVC


Qc=S*c_COPPER;
Qs=Ss*c_COPPER;

qs=1+L1;
QI=(pi/4)*(Di^2-Dc^2)*c_XLPE;
QI1=(pi/4)*(Di*Dc-Dc^2)*c_XLPE;
QI2=(pi/4)*(Di^2-Di*Dc)*c_XLPE;
QJ=(pi/4)*(Dj^2-Ds^2)*c_PVC;
%QJ2=(pi/4)*(Di^2-Di*dc)*c_PVC;     %not required


p1_VW=1/log(Di/Dc)-1/[(Di/Dc)-1];
p2_VW=1/[2*log(Dj/Ds)] - 1/[(Dj/Ds)^2-1];

Qi1=p1_VW*QI1;
Qi2=(1-p1_VW)*QI1;
Qi3=p1_VW*QI2;
Qi4=(1-p1_VW)*QI2;


Q1=Qc+p1_VW*Qi1;
Q2=(1-p1_VW)*Qi1+p1_VW*Qi2;
Q3=(1-p1_VW)*Qi2;
Q4=(Qs+QJ)/qs;
%Q5=Qj2/(1+lambda1);
```

```
TA=T(1)/2;
QA=Q1;
TB=T(1)/2+qs*T(3);
QB=Q2+[(qs*T(3))/TB]^2*(Q3+Q4);

%Eof
```

```
function [TA, TB, QA, QB] = long_trans(dc, Di, Ds, Dj, L1, S, Ss, T)
%
%
%  Function to calculate the Long Transient response of a cable
%
%
%  Usage:
%          [TA, TB, QA, QB] = long_trans(dc, Di, Ds, Dj, L1, S, Ss);
% Inputs:
%           dc = O/Diameter of the conductor
%           Di = O/Diameter of the insulation
%           Ds = O/Diameter of the screen
%           Dj = O/Diameter of the jacket
%           L1 = sheath loss factor
%           S  = Cros sectional area of conductor
%           Ss = Cros sectional area of screen
%           T  = array that hold T1, T2, T3

% Outputs:
%           TA = Thermal Resistance for 1st part
%           TB = Thermal Resistance for 2nd part
%           QA = Thermal Capacitance for 1st part
%           QB = Thermal Capacitance for 2nd part
%
%
%Short term transient response
c_COPPER = 3.45;        %specific heat for Copper
c_XLPE = 2.4;           %specific heat for XLPE
c_PVC = 1.76            %specific heat for PVC


Qc=S*c_COPPER;
Qs=Ss*c_COPPER;

qs=1+L1;
Qi=(pi/4)*(Di^2-dc^2)*c_XLPE;
Qj=(pi/4)*(Dj^2-Ds^2)*c_PVC;

p1=1/log(Di/dc)-1/[(Di/dc)-1];          % p1 = P
p2=1/[2*log(Dj/Ds)] - 1/[(Dj/Ds)^2-1];  % p2 = p'


TA=T(1);
TB=qs*T(3);
QA=Qc+p1*Qi;
QB=(1-p1)*Qi+[Qs+p2*Qj]/qs;

%Eof
```